JOURNAL
OF THE
WASHINGTON ACADEMY OF SCIENCES
VOL. 31 JUNE 15, 1941 No. 6

ASTROPHYSICS.—*The constitution of diffuse matter in interstellar space.*[1] OTTO STRUVE, Yerkes Observatory. (Communicated by EDWARD TELLER.)

THE EMPTINESS OF SPACE

On a clear moonless night we can see with the unaided eye somewhere between 2,000 and 3,000 stars. With an average pair of binoculars the number of visible stars is increased to about 10,000, and on long exposures taken with the largest existing telescope the number would be 2 or 3 billion. If we recall that the entire celestial sphere contains 41,253 square degrees and that the visible area of the full moon is about one-fifth of a square degree, we find that there are at least 10,000 stars within the reach of our most powerful instruments for every area of the sky equal to the full moon. If we remember also that the number of invisible stars—too faint to be recorded even with the 100-inch Mount Wilson reflector—is at least thirty times greater, and that near the Milky Way the concentration of stars is roughly one hundred times greater than at the poles of the galaxy, we find that in many regions of the Milky Way the apparent star density must be of the order of 30 million for an area equal to the disk of the moon. It is not surprising that on the best photographs of the Milky Way the images of the stars are so densely crowded together that they flow into one another and give the appearance of an almost continuous mass of stars.

But this impression is misleading. In reality the individual stars are separated by distances of several light years, and if we liken the stars to raindrops their average distances would have to be 40 miles to give us the right idea of the density within our galaxy of matter in the form of stars. For every cubic centimeter of stellar matter there are 10^{22} cubic centimeters of transparent space. Our galaxy is a relatively dense object. Since the average distances between neighboring galaxies are of the order of 10^6 light years, while their diameters are about 10^4 light years, it is easy to compute that within the diameter of the explorable universe—some 600 million light years—with its 10^8 separate

[1] The Eleventh Joseph Henry Lecture of the Philosophical Society of Washington, delivered on March 29, 1941. Received March 29, 1941.

galaxies and 10^{52} cubic centimeters of stellar matter, there are approximately 10^{28} cubic centimeters of transparent space for every cubic centimeter of stellar matter. The average density of a star like the sun is a little greater than that of water. Hence the density of stellar matter in the universe is only about 10^{-28} g/cm^3. A density of the order of 10^{-15} g/cm^3 is considered a high vacuum in ordinary laboratory technique.

But the question arises whether all matter in the universe is concentrated in the form of stars. It is possible that free atoms and molecules or small particles of dust float in interstellar space without completely obstructing the light of distant stars and galaxies. Eddington once remarked that although astronomers do not know much about interstellar matter they talk a great deal about it; they are like the guest who refused to sleep in a "haunted" room and who, when asked whether he believed in ghosts, replied: "I do not *believe* in ghosts, but I am *afraid* of them." It is probably no exaggeration to say that interstellar matter was the ghost that has haunted astronomers for the past hundred years. Until about 15 years ago they steadfastly refused to believe that there existed any such matter, even though direct photographs of the Milky Way gave unmistakable evidence of large regions in space where the light of distant stars is more or less completely cut off by the screening effect of cosmic dust clouds. They were afraid of the ghost because they thought it would play havoc with their elaborate theories of the structure of the Milky Way. These theories all depended upon an application of the inverse square law for the brightnesses of the stars. If two stars are of the same intrinsic luminosity, for example, if both have spectra that exactly match the spectrum of the sun, but one star is of apparent magnitude 5 while the other is of apparent magnitude 10, then the astronomers reasoned that since each step in magnitude corresponds to a ratio of 2.5 in the brightnesses of the stars, the fainter star sends us one hundredth as much light as the brighter and that, consequently, its distance must be ten times greater than that of the brighter star. It is obvicus that if a part of a star's light is intercepted by a screen of absorbing material, this computation would lead to erroneous results: the real distance of the faint star would be smaller than the one computed by means of the inverse-square law.

DISPERSION OF LIGHT IN SPACE

The first intimation of a possible effect of interstellar matter upon the propagation of light through cosmic space occurs in a letter by

Newton to Flamsteed, dated August 10, 1691. In the last sentence of this letter Newton, who was not an observer, asks the Astronomer Royal at Greenwich: "When you observe the eclipses of Jupiter's satellites I should be glad to know if in long telescopes the light of the satellite immediately before it disappears inclines either to red or blue, or becomes more ruddy or pale than before." The finite velocity of light had been measured in 1676 by Römer at Paris. He had used the predicted eclipses of the satellites of Jupiter and had taken advantage of the fact that Jupiter is at certain times much closer to the earth than at others. It was quite natural that Newton should try to find whether the velocity of blue and of red light is equal through interplanetary space, or whether an appreciable dispersion of the light takes place between Jupiter and the earth.

We have no record of Flamsteed's reply, and we do not even know whether observations were made to answer Newton's question. But astronomers gradually concluded that any possible dispersion was much too small to produce measurable effects in the satellites of Jupiter.

In 1855 Arago, in a course of public lectures at the Paris Observatory, applied the idea of Newton to the eclipses of distant binary stars whose orbit planes pass through the earth: "Let us then investigate what ought to be the density of this (hypothetical) interstellar gas in order that two rays, one red, the other blue, emitted at the same instant from a variable star, should arrive almost simultaneously at the earth notwithstanding the prodigious thickness of the matter traversed, notwithstanding the time of transmission which cannot be under three years; the solution of this simple problem of physics will astonish the imagination by its smallness." Arago gives no numerical results. He and others had "frequently examined periodic white stars in their different stages of brightness without remarking any appreciable coloring."

But these observations were made visually and were not very accurate. After the introduction of accurate photometric methods into astronomy, in 1908, it seemed for several years that a real positive effect of interstellar dispersion had been discovered independently by the Russian astronomer Tikhoff and the French astronomer Nordmann. These scientists found that when certain eclipsing variables are observed in red light the phase of central eclipse, or minimum light, occurs earlier than when the observations are made in blue light. For Algol (β Persei) the observed lag was 16 minutes $\pm$ 3 minutes. For λ Tauri it was 50 minutes and for RT Persei it was 4 minutes. This ap-

parent lag of blue light with respect to red light has been verified in many instances, and it is now known as the Tikhoff-Nordmann phenomenon. But, as Lebedeff had pointed out almost immediately after the announcement of Tikhoff's and Nordmann's discoveries, the distance of Algol is about 60 light years while that of RT Persei is 740 light years. Yet the nearer star has the longer lag of 16 minutes, so that if interstellar dispersion were responsible for the phenomenon the dispersion constant would have to be $16/4 \times 740/60 = 40$ times larger in the direction of Algol than in the direction of RT Persei. Modern determinations give somewhat different distances for the two stars, but the conclusion of Lebedeff has been shown to be true. Unless we make the absurd assumption that the dispersion constant is entirely different for different stars—even if they are located in the same part of the sky—the Tikhoff-Nordmann phenomenon must be due to some other cause.

The final word in the matter came from Shapley. For the stars of the globular cluster M5, whose distance is about 30,000 light years, or 3×10^{22} cm, blue light and yellow light arrived on the earth within an interval of -10 seconds $\pm$ 60 seconds. This corresponds to a difference of less than 0.3 cm/sec between blue and red light, and shows that the velocities are the same to at least one part in 10^{11}. We conclude that there is no measurable dispersion of light in interstellar space.

GENERAL ABSORPTION

Apparently the first astronomer to worry about the dimming of star light by intervening clouds of diffuse matter was Halley, around 1720. The argument was revived by Chéseaux in Switzerland, about 1744. Both astronomers pointed out that an infinite universe with an infinite number of self-luminous stars should cause the entire heavens to be ablaze with light—for no matter in which direction we should look, our line of vision would always ultimately reach the surface of some distant star. It was tacitly assumed that the distribution of the stars in space is uniform and that there are no dark stars. In 1823 the famous German astronomer Olbers expressed a similar view in the following words: "God has made the transparency of space imperfect in order to enable the inhabitants of the earth to study astronomy in its details . . . Without this, we should have no knowledge of the starry heavens; our own sun would be discovered only with difficulty by its spots; the moon and the planets would not be distinguishable, except as obscure discs upon a bright background, like the sun . . . " Fortunately all these dreadful consequences had been removed by the

foresight of the Creator who had introduced into interstellar space enough absorbing material to dim the light of the most distant stars so that the background is dark and not so brilliantly luminous as the sun.

It is futile now to speculate upon the scientific logic and the philosophical insight of these early astronomers. It is easy to see that even an infinite universe need not necessarily lead to a sky completely covered with stars, and the early arguments in favor of interstellar absorption are now, to say the least, unconvincing.

The mathematical theory of interstellar absorption was first precisely formulated by F. G. W. Struve, in Russia. His book *Études d'astronomie stellaire*, published in 1847, is the first really scientific study of the whole problem of interstellar matter. It forms the connecting link between the earlier semiphilosophical speculations of Olbers, Chéseaux, and Halley, and the brilliant theoretical researches of the last decades of the nineteenth century and the prewar years of the present century, principally by Seeliger, Kapteyn, and Schwarzschild. The common property of all these investigations was the tendency to smooth out the local irregularities in the observed structure of the Milky Way and to study an idealized or "typical" stellar system which retained certain characteristics of the Milky Way, such as galactic concentration, but purposely avoided the discussion of individual star clouds and dark regions.

Struve's work was based upon the star counts that Sir William Herschel had made with his giant telescopes in many different parts of the sky. These counts gave the numbers of all stars visible for every step in brightness, over a uniform field of the sky. The problem was to derive the true distribution of the stars in space and to find, if possible, whether there was an effect of absorption in space.

To consider this problem it is convenient to use the functions:

(1) $D(r)$—the density function, which measures the number of stars per unit volume, as a function of the distance from the sun, r.
(2) $\phi(M)$—the luminosity function, which measures the distribution of stars of different intrinsic luminosities.
(3) $i=f(r)$—the intensity function, which measures the apparent brightness of a star as a function of its distance from the sun, r.

The simplest assumptions that we can make and that we can test are

$$D(r) = \text{const.}; \phi(M) = \text{const.}; f(r) = \frac{i_0}{r^2}. \quad (1)$$

This is, essentially, what Olbers and his predecessors had assumed,

and it is fairly obvious that the appearance of the sky at once suggests one of two conclusions:

(*a*) the universe is finite, or

(*b*) there must be an appreciable absorption in space, in which case $f(r) \neq i_0/r^2$.

If we are not willing to abandon the inverse-square law, then it is easy to see that there must exist two simple, but important, statistical relations:

(1) The theoretical distances of stars of successive magnitude (apparent brightness) classes form a geometrical series whose coefficient is $(2.5)^{1/2}$

(2) The theoretical numbers of stars down to successive magnitude (apparent brightness) classes form a geometrical series whose coefficient is $(2.5)^{3/2}$

Since by definition the ratio of the observed intensities of two stars whose stellar magnitudes are m_1 and m_2 is

$$\frac{i_1}{i_2} = 2.5^{(m_1-m_2)}$$

and since by (1)

$$\frac{i_1}{i_2} = \frac{r_2^2}{r_1^2}$$

we have the first relation; when $m_1 - m_2 = 1$

$$\frac{r_2}{r_1} = \sqrt{2.5}\,. \tag{2}$$

Since, next, for uniform distribution of stars in space ($D(r) = \text{const.}$) the number of all stars down to each magnitude step is proportional to the volume of the spheres occupied by those stars which have the required apparent brightnesses, and since these volumes are proportional to r^3, we have, when $m_1 - m_2 = 1$:

$$\frac{N_2}{N_1} = (2.5)^{3/2} \tag{3}$$

or, for any value of $m - m_0$:

$$\log N_m = \log N_{m0} + 0.6\,(m - m_0). \tag{4}$$

Struve tested relation (4) by means of Herschel's star counts, which gave directly the values of N_m. There were large systematic departures in the sense that the observed N_m were smaller than those predicted

by the formula. Two possible conclusions presented themselves: (*a*) The assumption $D(r) = \text{const.}$ is wrong, and the density of the stars in space must decrease in all directions from the sun, or (*b*) the assumption $i = i_0/r^2$ is wrong, and there is an effect of interstellar absorption which makes i smaller than it would be without absorption. With regard to hypothesis (*a*), Struve writes: "Perhaps someone will say that there might be a gradual diminution in the star density in the principal plane, toward the outer boundaries of the Milky Way. But how much do we know concerning these boundaries? The Milky Way is for us absolutely impenetrable. What, then, is the probability that the sun should be located near the center of a disc whose extent is for us completely unknown? Let us recall, furthermore, that our study of the Herschel stars has led to the same average decrease in density, at right angles to the principal plane, which occurs in the neighborhood of the sun, up to the distance of stars of the 8th and 9th magnitude. From all these considerations I wish to state that we have discovered a phenomenon in which the extinction of star light unquestionably manifests itself." In place of the inverse-square law Struve adopts the relation

$$i = \frac{i_0}{r^2} e^{-\lambda r} \tag{5}$$

where λ is the coefficient of absorption. This is equivalent, according to Struve, to a loss of one stellar magnitude per 3,000 light years, or $\lambda = 3 \times 10^{-4}$ if r is expressed in light years. This value, obtained almost 100 years ago, is amazingly accurate. Modern results give an average loss of light of between 0.7 and 0.8 stellar magnitude per kiloparsec (3,000 light years). The agreement is as good as between individual results of modern observers.

It is strange that Struve's results were not universally accepted. The tendency was to assume that $\lambda = 0$ and to derive the resulting function $D(r)$. This procedure was adopted by Seeliger, Kapteyn, Schwarzschild, and Charlier. It resulted in a badly distorted picture of the Milky Way, with the sun near the center and the star density decreasing in all directions. Halm, in 1917, attempted to find λ under the assumption $D(r) = \text{const.}$, but his results were not accepted. As late as in 1923, Kienle, after a careful review of all available evidence, concluded that the loss of star light through absorption must definitely be less than 2 mag/kiloparsec and that it is probably less than 0.1 mag/kiloparsec.[2]

[2] Mag is used in this paper as the abbreviation for stellar magnitude.—EDITOR.

The first definite break in astronomical opinion came in 1930 when R. Trumpler published his results on open star clusters, obtained at the Lick Observatory. His work was based upon measurements of the diameters of galactic star clusters—groups of tens or hundreds of stars forming compact systems in which the motions of the individual members are all alike. Typical among these formations are the Pleiades, the Hyades, the cluster in Coma Berenices, and others. By observing the spectra of the members of clusters and their brightnesses Trumpler was able to prepare for each cluster a Hertzsprung-Russell diagram, in which the brightness of each star appears as the ordinate and the spectral type as the abscissa. In a diagram of this kind, as Russell had found many years ago, the majority of the stars are arranged in a definite narrow band—the so-called main sequence. Physically speaking, the main sequence of one cluster should be rather similar to the main sequence of another. But since the distances of the two clusters are, in general, not the same, it is necessary to shift the diagrams along the vertical coordinate in order to make the two sequences coincide. This displacement, measured along the vertical coordinate in stellar magnitudes, provides a measure for the relative distances of the two clusters. Distances determined in this manner are affected by absorption. Suppose we find that the vertical shift corresponds to 3 magnitudes. This means that all stars of the brighter cluster are $(2.5)^3 = 15.6$ times as intense as those of the fainter. If there were no absorption we should conclude from the inverse-square law that the fainter cluster is $\sqrt{15.6} = 3.95$ times as far away as the brighter cluster. But if absorption is present the real distance would be smaller. Trumpler conceived the idea of measuring the diameters of the clusters. He first made sure that he was measuring physically similar objects. If the brighter cluster had a diameter of 15′ the fainter should have a diameter of $15/3.95 = 3'.8$ provided the distances inferred from the Hertzsprung-Russell diagram are correct. From a large amount of very homogeneous material Trumpler concluded that the diameters of the fainter clusters were systematically too large. He suggested that there is an appreciable amount of interstellar absorption and derived for it a value of 0.67 mag/kiloparsec.

Among the many modern determinations of the average amount of interstellar absorption per unit distance, one of the most interesting is due to Joy at the Mount Wilson Observatory. The method depends upon determinations of radial velocities of Cepheid variables and upon the theory of the rotation of our galaxy, which predicts that the rotational component of motion of a star in the line of sight must be pro-

portional to the distance from the sun. This results from the nature of galactic rotation in a central field of force. The matter is complicated by the fact that the stars have their own individual motions. But these are probably distributed at random so that if we take average velocities for groups of Cepheid variables arranged according to apparent magnitude we should derive a series of values the ratios of which, after correction for foreshortening, give us directly the ratios of the true distances for the various groups. Now, the Cepheid variables, as everyone knows, have the remarkable property that their periods of light variation are exactly related to their intrinsic luminosities, so that if we know the periods of two such variables we can tell at once how much brighter one is than the other. If we use this criterion of absolute luminosity, together with the apparent brightness, we derive the distance. If there were no absorption the two procedures should give identical results. From the departures, which are conspicuous, Joy, and later R. E. Wilson, derived an absorption of about 0.6 mag/kiloparsec.

Another method depends upon counts of extragalactic objects in different parts of the sky. These distant galaxies are seen through the thickness of absorbing matter in our Milky Way, and their numbers are greatest near the two poles of the galactic circle, while near the plane of the galaxy the absorption is so great that no outer galaxies are seen through it. In intermediate galactic latitudes the absorptions are proportional to the cosecants of the latitudes. For example, at galactic latitude 10° the absorption is 1.4 mag, at 20° it is 0.7 mag, at 30° it is 0.50 mag, at 60° it is 0.29 mag, and at 90° it is 0.25 mag. The smooth manner in which these values progress has suggested to Seares the idea that we are here dealing with "a widely diffused absorbing stratum extending equally above and below the galactic plane." The zone of complete avoidance of galaxies, which is irregular in shape, is associated by Seares with the obscuring clouds in the Milky Way which give their distinctive irregular appearance to the star clouds.

SELECTIVE ABSORPTION

In 1895 Kapteyn discovered that the average color of stars in the Milky Way is bluer than outside of it. He suggested that this phenomenon might be caused by selective absorption, which should make those stars appear bluer for which the absorption was least. Since at that time there was no conclusive evidence of general absorption, Kapteyn could not know that the color observations would be in disagreement with other evidence by requiring the absorption to be

greatest at the poles of our galaxy. In 1904 DeSitter made a careful study of star colors and concluded: "True differences in the colors of the stars, or general absorption in certain spectral regions, or selective absorption by intervening cosmical clouds or nebulous masses, these are questions that can be put, but not yet answered." We now know that the intrinsically blue, hot stars have a much greater tendency to concentrate toward the galactic equator than do the cool, red stars. Hence the phenomenon of Kapteyn has no bearing upon the question of selective scattering.

However, the question was revived some years later when Turner and others noticed that in order to obtain photographic star images of equal densities for successive stellar magnitudes, it was not sufficient to increase the exposure times in the ratio of 2.5 for each step of one magnitude. In fact, it was found that the ratio of the exposure times is much more nearly 3 than 2.5—in spite of the fact that by definition a step of one magnitude signifies an intensity ratio of 2.5. In other words, the photographic density B is not a function of the product $(i \times t)$ alone, where i is the light intensity and t is the exposure time, but may be written as

$$B = f(i \times t)^p$$

where $0 < p < 1$. The quantity p is now known as Schwarzschild's exponent.

Tikhoff and Turner suggested that p had a cosmic significance. They argued that selective absorption will make the stars appear redder the greater their distances. But distant stars are, on the average, faint. Hence, faint stars are red, and must require relatively longer exposures on the blue-sensitive photographic emulsions—the only ones then used for these observations. Turner summarized the matter in the following words: "The fact that when the photographic exposure is prolonged in a ratio which ought to give stars fainter by five magnitudes, we only get four visual magnitudes" is an argument in favor of "the scattering of light by small particles in space."

The obvious thing would have been to check the result by means of visual observations made with the help of violet filters. There is no reason why this could not have been done. The test would have shown at once that the fainter stars are not appreciably redder and that the Schwarzschild exponent is not a measure of interstellar reddening.

The correct interpretation of p was given in 1909 by Parkhurst. It represents a characteristic property of the photographic emulsion and determines what we now call the reciprocity failure of the emulsion. It is different for different brands of emulsions.

A new attack upon the problem became possible with the development of accurate methods of photographic photometry. Miss Maury at Harvard had remarked in her work on the spectra of the stars that among representatives of a single class of spectrum there were some which were weak in violet light while others were strong. Kapteyn examined the available data on star colors and found that within narrow groups of spectrum those stars which were rich in violet light had large angular proper motions, while those which had little violet light had, at the same time, small proper motions. Since the angular proper motion of a star is a good statistical measure of distance, he concluded that the distant stars are reddened by absorption. Unfortunately, this conclusion was incorrect. It turned out later that another interpretation could be given. The stars examined by Kapteyn within any given group of spectrum were, through observational selection, all more or less similar in apparent brightness. Hence, the distant stars of each group were giants, while the nearby stars were dwarfs. Kapteyn could not have known, or even suspected, that the surface gravities of the giants are very much smaller than those of the dwarfs and that, consequently, the pressures of the former are one hundredth as great as those of the latter. Equal spectral types imply equal average ionization. But in a giant with its low atmospheric pressure the same degree of ionization is attained at a lower temperature than in a dwarf. Kapteyn had discovered what is essentially the basis of spectroscopic luminosities, but he had not found evidence in favor of space reddening.

In 1923 Kienle could only conclude that the coefficient of selective absorption must be less than 0.1 mag/kiloparsec. As we shall see, this result was unnecessarily pessimistic. Even before Kienle's paper was printed, in 1919, Russell had called attention to the fact that "the three most abnormally yellow stars of type B (ζ, o and ξ Persei) lie within 5° of one another, in a region full of diffuse nebulosity," and he had suggested that this might be caused by local selective absorption in some of the dark clouds of the galaxy. Several years later Hertzsprung compiled a list of abnormally yellow B stars, whose color excesses were larger than can normally be explained as a result of differences in absolute magnitude. This list was greatly enlarged by Bottlinger, and in 1926 the present writer found fairly convincing evidence "that the effect of reddening . . . is produced by light scattering in dark nebulae or in calcium clouds."

The modern evidence concerning selective absorption in interstellar space rests upon three types of observation:

(1) Color excesses of B-type stars determined photoelectrically by Stebbins, Whitford, and Huffer, or photographically by Seyfert and Popper. These results show a progressive reddening for the more distant stars. In setting the 82-inch McDonald telescope upon a faint B-type star I have often been amazed at the redness of these stars: their continuous spectra show energy distributions corresponding to some 4,000° or 5,000°, while their absorption lines correspond to a temperature of 20,000°.

(2) Observations of color indices of members of open clusters by Trumpler and his associates.

(3) Determinations of the energy distributions and colors of stars involved in dense clouds of absorbing matter, by Seares and Hubble, Baade and Minkowski, Henyey, etc.

An important quantity is the ratio of selective absorption to total absorption. Seares concludes from a discussion of all available data that:

Total absorption = 10 × selective absorption, for the diffuse stratum of interstellar matter, and

Total absorption = 5.7 × selective absorption, for the dark nebulae of the zone of avoidance.

The latter law corresponds to an absorption coefficient which is proportional to λ^{-1}. The departure from Rayleigh's λ^{-4} law was first established by Trumpler, and was then confirmed by Struve, Keenan, and Hynek. It is probable that some stars, observed by Baade and Minkowski in the Orion nebula, present appreciable departures from the smooth λ^{-1} relation, but the exact nature of these departures has not yet been explored.

DIFFUSE RADIATION

The existence of reflection nebulae, whose spectra are continuous and whose absorption lines are identical with those of the associated stars was demonstrated many years ago by V. M. Slipher. Since that time the present writer, Henyey, Elvey, Greenstein, and others have investigated in detail the character of the diffuse light that is scattered by dark nebulae and by interstellar space. The light is nearly of the same color as that of the illuminating stars; in the Pleiades the nebulosity is slightly bluer, but the difference between nebula and star is much less than that between the blue sky and the sun. This is in agreement with the λ^{-1} relation found from the absorption effects. The diffuse light is very little polarized, which all goes to show that the particles are too large for Rayleigh scattering. On the other hand, there is some evidence to show that the phase function of the particles throws

Fig. 1.—Region in Taurus, showing obscuring nebulae that radiate feebly by reflecting the light of the stars. (Photograph by E. E. Barnard.)

most of the light forward and does not show the "phases of the moon," as one would expect if the particles were larger than about 0.01 cm in radius. This conclusion rests upon a comparison of the diffuse surface brightness of dark nebulae of absorbing matter. These nebulae are illuminated by the light of all stars around them. The situation is somewhat analogous to the case of a spherical body which is illuminated from all sides. If the intensity of the general starlight is assumed to be uniform and equal to $L_1 = 56$ stars of magnitude 10.0 per square degree, if γ is the albedo of the particles, α is the phase angle, i is the angle of incidence and ϵ the angle of emergence, then the surface brightness of the nebula is

$$I = \frac{\gamma}{2\pi} L_1 \int \phi(\alpha) \frac{\cos i}{\cos i + \cos \epsilon} d\omega. \qquad (6)$$

This formula predicts that the rim of the nebula must be brighter than the center, but the amount of the difference depends upon the form of the phase function $\phi(\alpha)$. If we do not wish to make the albedo unreasonably large, we are compelled to adopt a forward throwing phase function. This suggests that the particles have radii smaller than 0.01 cm.

Sizes between 0.01 cm and 0.001 cm are excluded because of the absence of diffraction nebulosities surrounding stars that are seen through absorbing nebulosity. If the particles acted like water particles in clouds, of the required size, they should give rise to bright rings, which are often incorrectly called halos, the surface brightnesses of which may be computed. As a bright star seen through a thin cloud gives a halo, so the stars shining through dust clouds should produce halos. A search made by the writer some time ago yielded rather definite evidence that there is no halo formation. Hence the particles are smaller than 0.001 cm.

The interval of possible sizes for the majority of the particles has now been narrowed to between 10^{-3} and 10^{-5} cm. To go beyond this we must make use of the complicated theory of Mie for the scattering of light by small particles, and this has been done by a number of investigators, for example, by Shalén in Sweden and Greenstein in the United States. The most frequent sizes of the particles are slightly greater than 10^{-5} cm.

In connection with the problem of illumination of dense obscuring nebulosities, Struve and Elvey found in 1937 that the surface brightnesses of some of Barnard's dark nebulae are only about 0.03 mag fainter than the background of the sky between the stars in star

Fig. 2.—Dark nebula projected upon luminous gaseous nebula, in Orion. (Photograph by J. C. Duncan.)

clouds. If the star clouds were free of absorbing material the dark nebulae should be considerably more luminous. Hence we conclude that either the scattering efficiency (albedo) of the particles composing the nebula is very low, or there exists a large amount of diffuse radiation in the star clouds of the Milky Way. A direct observational test by

means of a photoelectric surface photometer was made by Elvey and Roach. They confirmed the correctness of the second alternative: there is a diffuse "galactic light" in the Milky Way, corresponding to about 57 stars of magnitude 10 per square degree, in the galactic plane. A careful study by Henyey and Greenstein has permitted them to subtract from the galactic light that part which comes from emission sources. In Cygnus, where the galactic light is strongest they find the diffuse radiation to be equivalent to 80 stars of magnitude 10 per square degree. In Taurus the galactic light is equivalent to only 35 stars of magnitude 10 per square degree.

Henyey and Greenstein consider the absorbing layer to be a slab of emitting and scattering matter, stratified along parallel planes. If the incident starlight and diffuse light has an intensity of L_1, each element of the absorbing material having an optical thickness $d\tau$, contributes to the observed galactic light the amount

$$\gamma d\tau \int L_1 \phi(\alpha) d\omega \tag{7}$$

where γ is the albedo of the particles. The formula is analogous to (6). The total surface brightness of the galactic light in a given direction is obtained by multiplying (7) by $e^{-\tau}$ and integrating over τ from 0 to the limiting optical thickness of the absorbing layer τ_0:

$$I = \gamma \int_0^{\tau_0} e^{-\tau} d\tau \int L_1 \phi(\alpha) d\omega = \gamma(1 - e^{-\tau_0}) \int L_1 \phi(\alpha) d\omega. \tag{8}$$

The quantity L_1 can be computed from star counts, provided we demand no refinements such as the variation of L_1 with τ. The phase function is not known. But it is clear that an isotropic distribution of the scattered radiation would make I larger than a strongly forward or backward throwing phase function. Indeed, at any given point on the slab of absorbing material the area of sky contributing to its illumination is greatest for $\alpha \sim 90°$. Hence a strongly forward throwing phase function will throw less radiation into the line of sight than an isotropic phase function. This presupposes that L_1 is uniform over the sky. In reality it is concentrated toward the Milky Way, and the integral must be evaluated numerically. In the region of Cygnus τ_0 must be very great. For all practical purposes we may assume that $\tau_0 = \infty$, so that

$$I_c = \gamma \int L_1 \phi(\alpha) d\omega. \tag{9}$$

Knowing L_1 we can compute I for phase functions having different

tendencies of throwing the light forward. We need not consider backward throwing functions because we have already eliminated them.

For the Taurus region

$$I_T = \gamma(1 - e^{-\tau_0}) \int L_1 \phi(\alpha) d\omega \cdot \tag{10}$$

Taking the ratio, we find

$$1 - e^{-\tau_0} = \frac{I_T}{I_c} = \frac{35}{80} = 0.44 \cdot \tag{11}$$

Since the integral $\int L_1 \phi(\alpha)\, d\omega$ is not strictly the same for the two regions Henyey and Greenstein derive a slightly different value. But we shall continue to use (11). Of course, τ_0 here refers to the Taurus region, where we evidently have relatively little material. In the Cygnus region the integral $\int L_1 \phi(\alpha)\, d\omega$ is about 72 stars of magnitude 10 in the case of an isotropic $\phi(\alpha)$; 80 stars of magnitude 10 for a moderately forward throwing ϕ; and about 135 stars of magnitude 10 for an extremely forward throwing ϕ. Since γ, the albedo, can not be greater than 1, we conclude that:

(1) the phase function must be at least moderately forward throwing, and

(2) the albedo must be at least $80/135 = 0.6$.

Indeed, when $\gamma = 1$, we have

$$I_c = \int L_1 \phi(\alpha) d\omega$$

and this is true only when ϕ is moderately forward throwing. If $\gamma < 1$, then ϕ must be even more forward throwing. For an excessively forward throwing ϕ, when all radiation is thrown forward, the integral is 135, so that $I_c / \int L_1 \phi(\alpha)\, d\omega = \gamma = 80/135 = 0.6$. If allowance is made for errors in the observations and for various refinements in the theory, Henyey and Greenstein find that the albedo must be greater than 0.3 and that the phase function must be strongly forward throwing.

STAR COUNTS

Our knowledge of the absorptions in individual regions of the Milky Way rests now largely upon star counts. The method first successfully used by Wolf and later improved by Pannekoek has in recent years received a new impetus through the work of Bok and his star-counting bureau at Harvard. The method consists essentially in the comparison of star counts made in obscured regions with those made in open regions. If there were no dispersion in the luminosities of the stars the interpretation of the results would be simple. The exist-

ence of $\phi(M)$ causes considerable complications, but Bok has developed a numerical procedure which is particularly adapted to the study of individual dark nebulae. A list of these nebulae prepared by Greenstein and quoted by Bok is given in table 1.

TABLE 1.—ABSORBING CLOUDS

Region	Area in square degrees	Distance in parsecs	Diameter in parsecs	Absorption in magnitudes
Taurus–Orion–Auriga...	600	145	65	1.1
Cepheus–Cassiopeia.....	450	500	170	0.7
Cygnus.....	85	700	130	1.5
Ophiuchus–Scorpius....	1050	125	80	0.9
Vela.....	105	600	120	1.0(?)

Shalén has used similar methods, but has limited the material to a narrow range of spectral type. Morgan and, quite recently, O'Keefe have made considerable progress by studying the spectroscopic luminosity criteria of B-type stars and by deriving the best possible individual distances for highly reddened stars.

DYNAMICAL CONSIDERATIONS

An indirect method of estimating the density of interstellar matter rests upon Oort's study of stellar motions at right angles to the plane of the Milky Way. The motions of the stars in the galactic plane are governed largely by the mass of the galactic nucleus. But the motions across the galactic plane are determined almost wholly by the distribution of mass in the vicinity of the sun. From the observed radial velocities Oort computes the space motions of the stars. The Z-components are then analyzed with regard to the distances of the stars from the galactic plane. This leads to a determination of the accelerations in the Z-coordinate, and these depend upon the density of matter in the vicinity of the sun. The data of observation are best satisfied for an average density of 0.092 solar mass per cubic parsec, which is equivalent to 6.3×10^{-24} g/cm^3. Oort finds that the luminous stars in the solar neighborhood account for 0.038 solar mass per cubic parsec. Hence, the difference, or 0.05 solar mass per cubic parsec, must be due to dark stars and to diffuse matter in interstellar space. This corresponds to a density of 3×10^{-24} g/cm^3—the famous Oort limit for the density of interstellar matter.

This leads to an estimate of the upper limit for the radius r of the particles. If the absorption were due to obscuration we would have for the absorption coefficient $n\pi r^2$, where n is the number of particles per cubic centimeter. With Trumpler's value of the absorption we write

$$2.5 \log_{10} e^{-n\pi r^2 l} = 0.7, \qquad (12)$$

where l is equal to 3×10^{21} cm. Let the density of each particle be $d=5$ g/cm^3. Then Oort's limit

$$3 \times 10^{-24} \text{ g/cm}^3 = n \frac{4}{3} \pi r^3 d. \qquad (13)$$

Combining (12) and (13), we find

$$r = 10^{-2} \text{ cm}.$$

This is an upper limit for the average radius of the particles and not an estimate of the sizes of those particles which are mostly responsible for the scattering of light.

INTERSTELLAR GASES

In 1904 Hartmann found that the absorption lines of Ca II in the spectrum of the double star δ Orionis fail to take part in the periodic oscillations of the other lines. He eliminated the obvious explanation that the stationary Ca II lines come from a very massive secondary component of the binary system and concluded that "at some point in space in the line of sight between the sun and δ Orionis there is a cloud which produces that absorption, and which recedes with a velocity of 16 km/sec." Since that time other atoms and molecules have been found to originate in interstellar space. Among them are Na I, Ca I, K I, Ti II, CN, and CH. Na I was found many years ago by Miss Heger at the Lick Observatory; Ca I, K I, and Ti II were found by Adams and Dunham; CH was measured by Dunham in 1937 and was identified by Swings and Rosenfeld; CN is due to Adams and McKellar. There are several unidentified absorption lines from interstellar matter. Among them are sharp lines at λλ 3957 and 4233.[3] These lines are very prominent in several B-type stars, for example ζ Ophiuchi, and are clearly of interstellar origin. There are also a number of diffuse absorption lines, or bands, discovered by Merrill and by Beals and Blanchet. They are as yet unidentified, but there is evidence that their intensities are closely correlated with color excess, so that they are perhaps produced by the dust particles. The wave lengths of these broad lines are λλ 4430, 5780, 5796, 6284, and 6614.

The remarkable thing about the identified lines is that they all originate from the lowest level of each atom. Even if the level is multiple, as in Ti II, only those numbers of the resonance multiplet appear which come from the lowest sublevel. Forbidden transitions depopu-

[3] The symbols λ and λλ are used as abbreviations for "wave length" and "wave lengths," respectively; these wave lengths are expressed in Ångstrom units.—EDITOR.

late the higher levels to such an extent that absorption lines originating in them are not seen.

One of the substances which might be expected to produce interstellar absorption lines is Fe I. Swings and I searched for it in the fall of 1939 on our spectrograms of early-type stars. The lowest level is a^5D and there are several lines of different multiplets which arise from it. We searched in B-type stars for the strongest expected lines, λλ 3719.94, 3440.63, and 3859.92. The first is in the wing of the hydrogen line H_{14} 3721.94. A search on Process plates taken with the quartz spectrograph of the McDonald Observatory for several stars in which interstellar Ca II is strong, for example ξ Persei, χ Aurigae, χ^2 Orionis, α Camelopardi, strongly suggests that λ 3720 is present. But the line is weak and we are not prepared to make a positive identification with the material now available to us.

The intensities and radial velocities of the interstellar lines of Ca II and Na I have been measured in many stars. There is a pronounced correlation between distance and intensity, first found by the present writer, which has served to give us an independent method for finding the distances of hot stars. The method has been discussed by a number of astronomers; some believe that the density of interstellar calcium or sodium is not sufficiently uniform throughout space to give reliable information regarding the distances. Dunham has even announced from measurements in α Virginis (distance 53 parsecs) and η Ursae Majoris (distance 66 parsecs) that "there is probably a region of lower than average density close to the sun." Dunham also thought that there was a difference in the average density of 2.4×10^{-19} ionized calcium atoms in the direction of α Virginis and that of 5.2×10^{-11} atoms in the direction of η Ursae Majoris. This latter conclusion depends upon the adopted distances of the stars, which may be somewhat in error, as Morgan has recently demonstrated. On the whole, it may be said that distances derived from the intensities of interstellar lines are fairly reliable, provided a correction is applied to take care of the concentration of the gas toward the galactic plane.

There is also a tolerably good correlation between line intensity and color excess. But each of these quantities is much better correlated with distance, so that we are certain that condensations of reddening particles are not necessarily accompanied by increased densities of interstellar atoms.

The radial velocities of the interstellar lines show (*a*) a relatively small tendency toward peculiar motions and (*b*) a conspicuous relation with galactic rotation, the line of sight component of the latter being

exactly one-half of its value derived from the corresponding stars. In view of the small peculiar motions the galactic rotation effect may be used for deriving the distances of the stars. However, there are numerous cases of stars showing double interstellar lines. These have been explained as being caused by two separate clouds of atoms, each having its own motion.

Whenever the star lines are broad and diffuse the attribution of a sharp line to interstellar matter is quite unambiguous. But when the star lines are sharp the distinction is not always easy, except in spectroscopic binaries. There has been in recent years too much of a tendency to take it for granted that all sharp Ca II lines in spectral types B3 and earlier are interstellar. I have recently measured the Ca II line λ 3933 in the luminous B1 star β Canis Majoris and have found on Texas Coudé plates that the line shares the oscillation of the star lines. Morgan has remarked that especially in supergiant stars the stellar calcium lines may sometimes persist as far as B0.

A problem of great interest and one that has not yet been completely solved is that of the line contours of the interstellar atomic lines. These contours are deep and become appreciably broadened in the more distant stars. It was at first suggested, by Unsöld, Struve, and Elvey, that the broadening may be caused by the effect of galactic rotation, and Eddington attempted to explain the relative intensities of Ca II to Na I as a result of the corresponding curves of growth. However, observations, principally by Merrill, Wilson, Sanford, and others at Mount Wilson, have shown that there are no striking differences in line contours of distant stars located (in galactic longitude) near the nodes and near the maxima or minima of the curve of galactic rotation. Clearly, near the nodes the broadening can not be due to galactic rotation, and in the absence of other Doppler effects, it must be due to the natural widening of the line by radiation damping. It is probable that a small effect of this kind does exist, but there can be no doubt that the lines in the two groups of stars are much more nearly alike than the theory predicts. Hence it may be regarded as certain that the contour is determined largely by turbulence, which masks the galactic rotation broadening except, perhaps, in the most distant objects. The average turbulent velocities have not been accurately determined, but they are probably of the order of 10 to 20 km/sec, in the line of sight.

THE IONIZATION PARADOX

In 1926 Eddington investigated the ionization of the interstellar gas. Since it is reasonable to suppose that the gas is in a steady state,

we write for the equilibrium of Ca I and Ca II:

$$\text{No. of ionizations} = \text{No. of recombinations} \tag{14}$$

or

$$\text{No. of bullets of quanta disrupting atoms} = \text{No. of ions colliding with electrons and forming atoms.}$$

This is equivalent to:

$$N_1 \times \text{No. of quanta of appropriate power} = N_2 N_e \times \text{function of cross sections for collisions and of velocity or temperature.} \tag{14a}$$

In other words,

$$N_1 \phi(\text{Ioniz. pot.}, T) = N_2 N_e f(T, \sigma)$$

or

$$\frac{N_2}{N_1} N_e = F\ (\text{Ion. Pot.}, T).$$

This is in effect Saha's ionization equation. In thermodynamic equilibrium it is

$$\log \frac{N_2}{N_1} N_e = -\chi \frac{5040}{T} + 1.5 \log T + 15.38 + \log \frac{2u_2}{u_1} \tag{15}$$

where χ is the ionization potential and u_2, u_1 are the statistical weights of the ground states of the ion and the atom, respectively. In the interstellar gas the radiation is very greatly diluted, and its spectral composition corresponds to the integrated effect of all the stars. In (14) or (14a) the left side is proportional to the density of the radiation and this is equal to Planck's function for the appropriate average temperature and to the dilution factor W, which measures the departure from thermodynamic equilibrium. W is equal to the ratio of the available density of radiation to that which would be available if for the appropriate temperature T there existed thermodynamic equilibrium. The right side of (14) or (14a) is not altered. We can, therefore, write the ionization equation for interstellar matter in the following manner:

$$\frac{N_2}{N_1} N_e = W \times F\ (\text{Ion. Pot.}, T),$$

or

$$\log \frac{N_2}{N_1} N_e = -\chi \frac{5040}{T} + 1.5 \log T + 15.38 + \log \frac{2u_2}{u_1} + \log W. \tag{16}$$

This, however, presupposes that the distribution of velocities of the electrons in the gas is Maxwellian and corresponds to the same tem-

perature T, as the one which results from the summation of the energy curves of all stars. This will not, in general, be the case. A more elaborate treatment for an electron temperature T_e gives

$$\log \frac{N_2}{N_1} N_e = -\chi \frac{5040}{T} + 1.5 \log T + 0.5 \log \frac{T_e}{T} + \log W. \quad (17)$$

Finally, in some applications of the theory it is necessary to allow for the gradual diminution of the ionizing radiation by absorption in the gas. This introduces an extra factor of $e^{-\tau}$ in the left side of (14) and (14a), so that our final expression is

$$\log \frac{N_2}{N_1} N_e = -\chi \frac{5040}{T} + 1.5 \log T + 0.5 \log \frac{T_e}{T} + \log W + \log e^{-\tau}. \quad (18)$$

All logarithms are to the base of 10. The dilution factor can be determined from the observed distribution of the stars. Eddington proceeds in the following manner. He determines the appropriate temperature by summing the energy curves of all stars in the approximate wave length range where the ionization of calcium is produced. This turns out to be about 15,000°. In thermodynamic equilibrium Planck's formula gives an energy density of 387 erg/cm³ for 15,000°. In interstellar space conditions are different. We know that the sun radiates 3.8×10^{33} erg/sec and that a star of bolometric absolute magnitude 1.0 radiates 36 times as much, or 1.4×10^{35} erg/sec. By definition at a distance of 10 parsecs the absolute magnitude of a star is equal to its apparent magnitude. If we spread the energy radiated per second by our first magnitude star over a sphere of 10 parsecs in radius we have

$$\frac{1.4 \times 10^{35}}{4\pi \times 100 \times 9 \times 10^{36}} = 10^{-5} \text{ erg/cm}^2 \text{ sec.}$$

The energy density is obtained by dividing this by c. But the total of all star light is equivalent to 2,000 stars of the first apparent magnitude. Hence the radiation density in interstellar space is

$$\frac{2000 \times 10^{-5}}{3 \times 10^{10}} = 7 \times 10^{-13} \text{ erg/cm}^3.$$

The dilution factor is

$$W = \frac{7 \times 10^{-13}}{387} = 2 \times 10^{-15}.$$

More accurate values have been derived by Gerasimovič and Struve, by Greenstein, and by Dunham.

We can now proceed and compute N_2/N_1 for Ca II/Ca I by substituting numerical values into (18). The question is what to use for N_e. Eddington determines a very rough value for the density of interstellar matter by assuming that the gaseous nebulae are condensations of the interstellar medium and that the theory of isothermal gas spheres may be applied to these objects. This gives $\rho = 10^{-24}$ g/cm^3. Since the electron pressure is not very different from the total gas pressure this estimate gives N_e and hence also N_2/N_1.

Gerasimovič and Struve proceeded in a different manner. In the absence of any information regarding N_e they assumed that all elements are equally effective in producing electrons in interstellar space, so that N_e could be determined from the equation

$$pN_e = N_2(\mathrm{Ca}^+) + 2N_2(\mathrm{Ca}^{++}), \tag{19}$$

where $p = 0.015$ is the percentage abundance of calcium by atoms in the crust of the earth. This equation led to a very small value of $N_e = 10^{-3}$, which in turn gave a very high degree of ionization. The ionization of calcium and sodium derived by Gerasimovič and Struve is shown in table 2.

TABLE 2.—IONIZATION OF CALCIUM AND SODIUM
($N_e = 10^{-3}$)

Calcium		Sodium	
Ca	3×10^{-11}	Na	2×10^{-7}
Ca^+	7×10^{-6}	Na^+	1
Ca^{++}	1	Na^{++}	6×10^{-3}
Ca^{+++}	2×10^{-3}	—	—

Since the observed line intensities of Na I and Ca II are very similar, the table suggests that in cosmic clouds sodium atoms must be 300 times more abundant than atoms of calcium. On the earth the abundance of sodium is only about 1.3 times that of calcium. This ratio is probably true of other cosmic sources, and it is strange that in interstellar space the abundance of sodium should be several hundred times greater. This result is similar to that of Eddington. It formed a serious barrier to further work.

SOLUTION OF THE PARADOX

In 1926, when Eddington's work was published, and in 1929, when Gerasimovič and Struve published their computations, there was no reason to doubt that calcium was a very abundant substance. The fact that calcium and sodium were the only elements then known in the spectrum of interstellar matter, combined with the great inten-

sity of the calcium lines in the solar chromosphere and in prominences, led quite naturally to the idea of "calcium clouds," which were believed to consist largely of calcium. The idea advanced by Gerasimovič and Struve that the abundance of calcium might be only 1 or 2 percent was revolutionary in 1929.

However, later work on the composition of the sun by Russell a short time afterward established beyond doubt the tremendous preponderance of hydrogen over all other elements. Hence it became necessary to review the problem of the ionization of interstellar matter with the idea that hydrogen might supply the overwhelming majority of the free electrons.

The basis of the new discussion consists of Dunham's recent measurements of the intensities of the lines of Ca I 4226 and Ca II 3933 in several stars. From these intensities it is possible to derive the numbers of atoms per cm² of Ca^+ and of Ca, and thus determine by observation the ratio N_2/N_1. This was done independently by Struve and by Dunham. The ionization equation then leads directly to a determination of N_e. Struve finds 30; Dunham obtains values of 14.4 and 7.3, depending upon which of two assumptions he uses for the integrated ultraviolet radiation of all stars. Within the past few days we have received a communication from Bates and Massey, of Northern Ireland, who have corrected the ionization formula (18) for the fact that the ionization processes take place almost exclusively from the ground level of the Ca atom, while in recombination many atoms first find themselves in higher energy states, from which they rapidly cascade downward to the ground level. This correction effectively reduces the ionization so that the same observed ratio N_2/N_1 can now occur at a lower electron density N_e. The factor is approximately equal to 6. Taking Dunham's upper value, 14.4, we find:

$$N_e = 2.4 \text{ cm}^{-3}. \tag{20}$$

We shall see in the next section that there is a good confirmation of this value from observations of interstellar hydrogen emission lines. The uncorrected value of N_e is sufficient, as I pointed out in 1939, to greatly improve the Na/Ca paradox. Using this N_e, and adjusting W and T for the required ionization potentials, we compute:

$$\left.\begin{aligned} \frac{N_2(Ca^+)}{N_1(Ca)} &= 100 \quad \text{and} \quad \frac{N_3(Ca^{++})}{N_2(Ca^+)} = 10 \\ \frac{N_2(Na^+)}{N_1(Na)} &= 270, \qquad \frac{N_3(Na^{++})}{N_2(Na^+)} = 0 \end{aligned}\right\}. \tag{21}$$

From the equivalent widths of Ca K and Na D and the corresponding distances, Wilson and Merrill found

$$N_1(\mathrm{Na}) = 3 \times 10^{-9}\ \mathrm{cm}^{-3}, \tag{22}$$

while for Ca K, Merrill and Sanford found

$$N_2(\mathrm{Ca}^+) = 9 \times 10^{-9}\ \mathrm{cm}^{-3}. \tag{23}$$

Combining (21) with (22) and (23) we obtain the total numbers of sodium and calcium atoms:

$$\left.\begin{aligned} N_1(\mathrm{Na}) + N_2(\mathrm{Na}^+) &= 8 \times 10^{-7}\ \mathrm{cm}^{-3} \\ N_1(\mathrm{Ca}) + N_2(\mathrm{Ca}^+) + N_3(\mathrm{Ca}^{++}) &= 1.2 \times 10^{-7}\ \mathrm{cm}^{-3} \end{aligned}\right\}. \tag{24}$$

Sodium is about 7 times as abundant as calcium. Dunham finds a larger ratio,

$$\frac{\mathrm{Na}}{\mathrm{Ca}} = 25, \tag{25}$$

but even this is very much better than the discrepancy of 300 found in the earlier work. Strömgren suggests that the small remaining inconsistency of (25) with terrestrial data will disappear when the correction of Bates and Massey is applied to Na, as well as to Ca. Since the theory is difficult, expecially in not being able to give us very reliable values of T and W, we may consider the paradox of the ionizations as having been eliminated. Moreover, we must remember that the determinations in (22) and (23) rest upon the curves of growth for Ca and Na, and these are still incompletely known. Finally, the distances of the B stars are not accurately known.

INTERSTELLAR HYDROGEN EMISSION

We have already expressed the suspicion that the large value of N_e may come from the ionization of interstellar hydrogen. Consider the ionization of hydrogen. If we disregard the factor $e^{-\tau}$ in (18) and set $T_e = T$, we find with the appropriate values at $\lambda = 900$ A, viz. $T = 25{,}000°$, and $W = 10^{-17}$

$$\frac{N_2(\mathrm{H}^+)}{N_1(\mathrm{H})} \approx 10. \tag{26}$$

Since W and T are uncertain, this value is only a rough approximation.

The only lines of hydrogen which are accessible to observation are those of the Balmer series. Let us see how many H atoms we must

have in order to account for the value of N_e which we have derived from the calcium absorption lines. For simplicity let us use not the final result (20) but a value which is close to that derived by Dunham, namely

$$N_e = 10 \text{ cm}^{-3}.$$

Evidently, since $N_e = N_2(H^+)$ we conclude from (26) that we have in space one neutral atom of H per cm³. The question arises whether there is any chance of observing the bright H line in interstellar space.

We first compute the numbers of atoms in the third quantum level. Since this level is not metastable the population is proportional to W, so that

$$\frac{n_3}{n_1} = We^{-(h\nu/kT)} \tag{27}$$

With $W = 10^{-17}$ and $e^{-h\nu/kT} = 10^{-2}$ we have

$$n_3 = 10^{-19} \text{ cm}^{-3}. \tag{28}$$

Consider now the depths of space. Our Milky Way extends to tens of thousands of parsecs from the sun, but in effect the more distant regions are cut off by obscuring nebulosities. We can make only a rough guess as to the effective thickness of the visible layer:

$$D = 1{,}000 \text{ light years} = 10^{21} \text{ cm}. \tag{29}$$

Hence we shall have

$$n_3 D = 10^2 \text{ atoms/cm}^2. \tag{30}$$

The question arises: Can the emission of 100 hydrogen atoms per cm² be observed? The energy emitted by the layer is

$$n_3 D h\nu A_{31}$$

where $h\nu = 0.5 \times 10^{-11}$, $A_{31} = 0.5 \times 10^8$, and $n_3 D = 100$. This is

$$n_3 D h\nu A_{31} \approx 10^{-2} \text{ erg/cm}^2 \text{ sec}.$$

This is considerably brighter than the limit of human vision for surface brightnesses. The latter is roughly equivalent to one star of magnitude 9 per square degree. Since the apparent magnitude of the sun is -26, and since it covers about one-fifth of a square degree this means that we can detect surface brightnesses which are 35 magnitudes or about 10^{14} times as faint. The total radiation of the sun is about 10^{11} erg/cm² sec. Our eyes are sensitive to only a fraction of this, let us say to $\frac{1}{3}$. Hence the minimum surface brightness we can see is

$$\frac{2 \times 10^{10}}{10^{14}} = 2 \times 10^{-4} \text{ erg/cm}^2 \text{ sec.}$$

This is a fiftieth as faint as the expected brightness of the interstellar hydrogen emission. There is all reason to search for it. This was done a few years ago at the McDonald Observatory, with a specially constructed nebular spectrograph of great efficiency. The instrument consists of a narrow plane mirror, which acts as the slit. The light from the sky is reflected by the slit-mirror along the direction of the polar axis. At a distance of 75 feet it is intercepted by a plane mirror and returned to the prism box and f/1 Schmidt camera. Each spectrum is accompanied by a comparison spectrum from some other part of the sky.

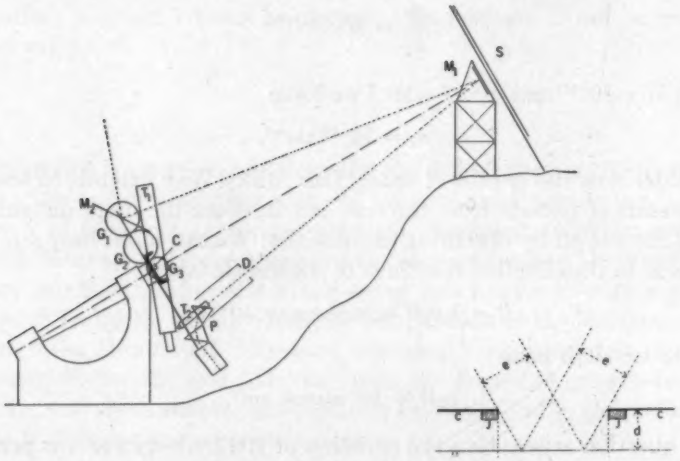


Fig. 3.—Nebular spectrograph of the McDonald Observatory. M_2 = narrow plane mirror acting as slit; M_1 = stationary plane mirror; P = prisms over camera; T = guiding telescope.

The results of the observations numbering nearly 80 long exposures show that—

(1) There are large regions in the Milky Way where H, [O II] 3727, [N II] 6548, 6484, and occasionally [O III] N_1 and N_2 appear in emission.

(2) These nebulae show but little concentration toward individual early-type stars, thereby differing conspicuously from ordinary gaseous nebulae.

(3) There is no emission at high galactic latitudes.

(4) The emission regions of H in Cygnus, Cepheus, and Monoceros are fairly sharply bounded on the outside. They are roughly circular

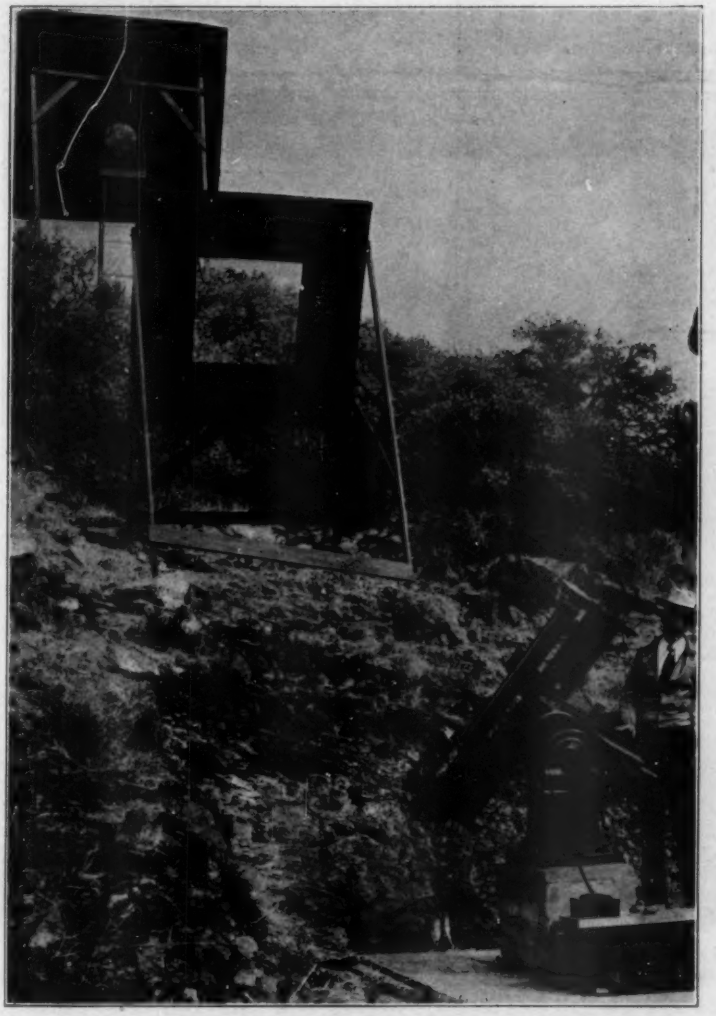
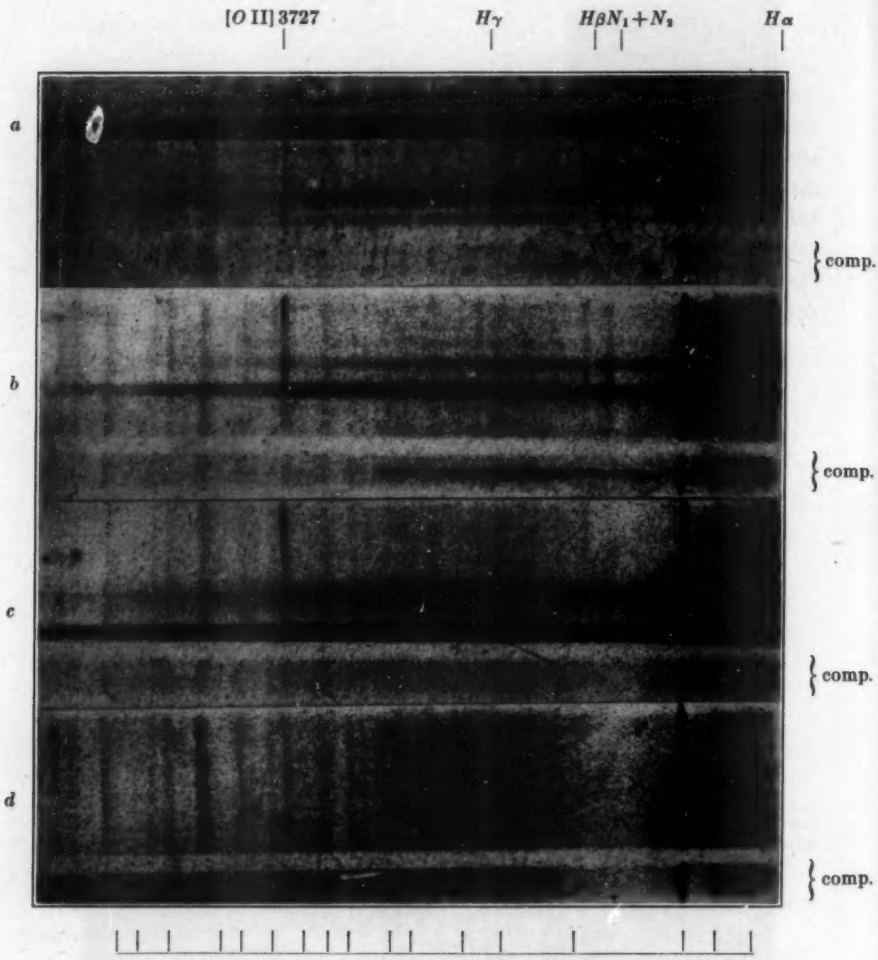


Fig. 4.—Nebular spectrograph of the McDonald Observatory.

in appearance. The intensity drops somewhat from the inner parts of each region toward the outer boundary, but this variation is relatively small.

(5) Whenever [O III] is seen in emission, it occurs in the central parts of the H regions, without any sharp boundaries.



AURORAL LINES

(*a*) Guiding star: 56° 2604. Nebula IC 1396
(*b*) Guiding star: 60° 504. Loose cluster
(*c*) Guiding star: 59° 559. Loose cluster
(*d*) Guided 6′ south of 29° 741

Fig. 5.—Spectra of Milky Way regions showing emission of H, [O II] and [O III] superimposed over spectrum of night sky.

(6) The H regions are probably associated with groups of O-type stars. This is demonstrated in Figs. 7 and 8 where the spectroscopic results are shown at the top, the distribution of the O stars at the bottom. The emission regions are shown by solid circles. Absence of emission is denoted by open circles.

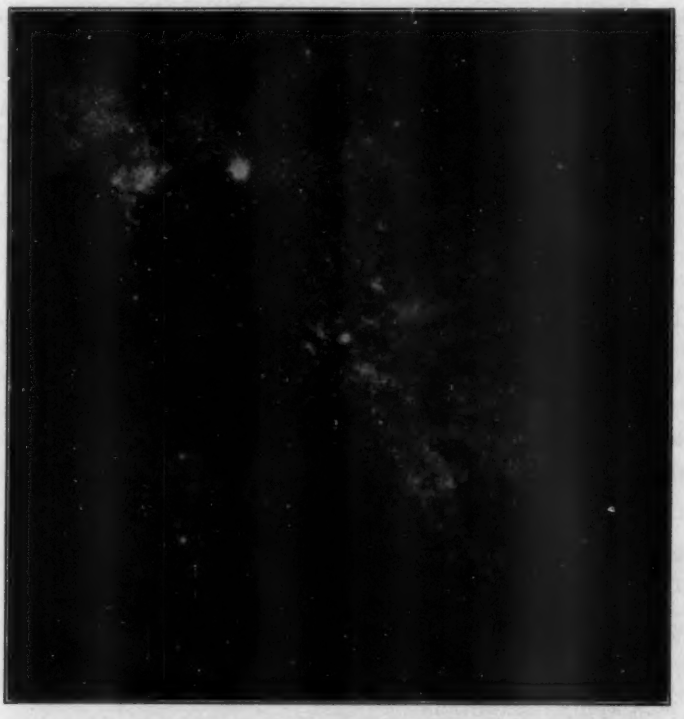


Fig. 6.—Milky Way in Cygnus. A large part of this area covering nearly 400 square degrees shows emission lines of H and [O II].

(7) The ratio in intensity [O II]/(H+[N II]) is large in Monoceros and Canis Major and small in Cygnus, Cepheus, and Sagittarius. This effect demonstrates a conspicuous difference between the physical conditions of the emission regions in two different parts of the sky.

(8) Some of the emission regions show a slightly milky background on the direct photographs of Ross and Barnard, but there are other regions of similar milky appearance which shine by reflected light.

(9) The hydrogen emission regions sometimes cover dark markings while in other instances the emission does not seem to extend over the

dark nebulosities. In the Taurus region there is no emission in the dark clouds, except in the immediate vicinity of bright O and early B stars. In the Ophiuchus nebulosities emission is seen only near the B1 star σ Scorpii. The other bright stars, of type B3, produce only reflection nebulae.

(10) Slipher reports that in the region $\alpha = 18^h\ 8^m$, $\delta = -18°\ 16'$ the emission of H covers not only the star cloud, but also the dark marking B92.

The sizes of the emission regions are of the order of $s_0 = 7°$ for the one around λ Orionis and $s_0 = 5°$ for the one in Cygnus. Assuming reasonable absolute magnitudes for the associated O stars we find the following linear dimensions:

Region	Radius
near λ Orionis	40 parsecs
Cygnus	130 parsecs
Monoceros	85 parsecs

The intensities of the observed hydrogen lines may be used to compute the number of atoms per cm^2 in the third energy level. In principle this is simple and can be done by reversing the procedure of the first part of this section. In practice there are many difficulties because we are dealing with an extremely faint light source. A fairly good average result from two independent series of observations is

$$n_3 = 5 \text{ cm}^{-2}.$$

Assuming $s_0 = 300$ parsecs (for which we shall see the justification later)

$$N_3 = \frac{5}{3 \times 10^2 \times 3 \times 10^{18}} = 5 \times 10^{-21} \text{ cm}^{-3}. \tag{31}$$

We next apply the formula

$$\frac{N_3}{N_1} = \frac{g_3}{g_1} W e^{-(h\nu/kT)},$$

which gives

$$N_1 = 3 \times 10^{-2} \text{ cm}^{-3}.$$

Allowing for the ionization, as in (26):

$$\frac{N_2(H^+)}{N_1(\text{H})} = 6,$$

we have

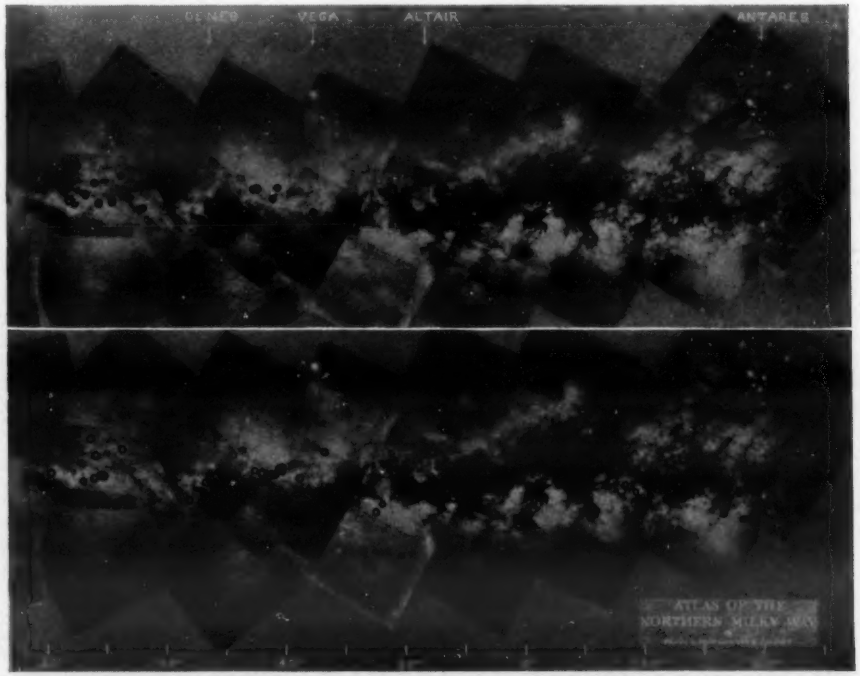


Fig. 7.—Summer Milky Way. At the top, regions showing emission of H and [O II] are plotted as solid circles. At the bottom, the known stars of spectral type O are plotted as open circles. The composite map was made by Miss Mary R. Calvert from the Atlas of the Milky Way by F. E. Ross and Mary R. Calvert.

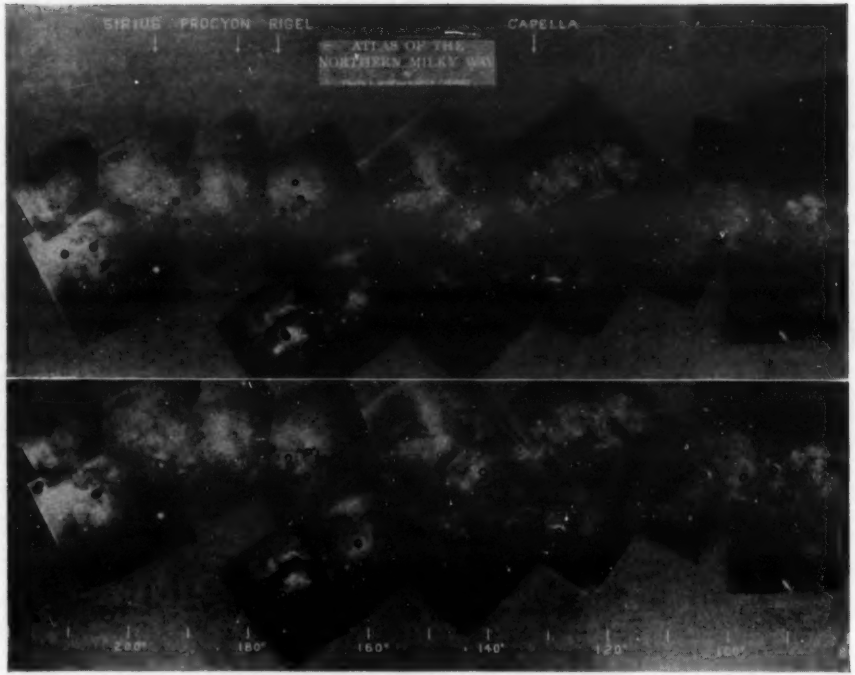


Fig. 8.—Winter Milky Way. At the top, regions showing emission of H and [O II] are plotted as solid circles; regions without emission are plotted as open circles. At the bottom the known stars of spectral type O are plotted as open circles.

$$N_2(H^+) = 0.2 \text{ cm}^{-3}.$$

But we should not have used the three-state problem. Evidently several other H levels will contain approximately the same populations as the third level. In fact, the second level may even be overpopulated. Strömgren has allowed for this effect accurately, but we shall simply estimate that the error due to the neglect of other excited levels corresponds to a factor of 10. Then the total number of hydrogen atoms is:

$$N_2 \approx N_e \approx N(H) = 2 \text{ cm}^{-3}.$$

From his detailed analysis which is based upon my and Elvey's observational data Strömgren finds

$$N(H) = N_e = 3 \text{ cm}^{-3}. \tag{32}$$

This agrees closely with the value derived from calcium.

STRÖMGREN'S THEORY

The significant element of this theory is the retention of the term $e^{-\tau}$ in the ionization formula (18):

$$\frac{N_2(H^+)}{N_1(H)} N_e = C \times \frac{1}{s^2} e^{-\tau}, \tag{33}$$

because $W = R^2/4s^2$. The constant C involves the ionization potential of H, the temperatures T and T_e and the radius of the exciting star R. Since presumably almost all free electrons came from H

$$N_e = N_2(H^+). \tag{34}$$

The optical depth τ is measured near the limit of the Lyman series:

$$d\tau = N_1(H) a_\nu ds, \tag{35}$$

where a_ν is the continuous absorption coefficient near λ 900 per neutral hydrogen atom. This quantity is known. In our ionization equation

$$\frac{[N_2(H^+)]^2}{N_1(H)} = C \times \frac{1}{s^2} e^{-\tau} \tag{36}$$

the ionization decreases with increasing distance from the ionizing star. Since a_ν is small this decrease is at first mainly caused by $1/s^2$, because for small s, the factor $e^{-\tau}$ is close to 1. But as the distance increases $e^{-\tau}$ becomes more important. Because of the exponential it causes a very abrupt change in ionization, producing a sharp bound-

ary beyond which H is almost completely neutral and inside of which it is almost entirely ionized. The radius of this boundary, s_0, can be computed. It depends upon the temperature and radius of the ionizing star and upon the density of hydrogen, $N(\mathrm{H}) = 3$ cm^{-3}. Physically what happens is this: "In the immediate neighborhood of a star, interstellar hydrogen will be ionized. With increasing distance from the star the proportion of neutral hydrogen atoms increases, and hence the absorption of the ionizing radiation increases. Ultimately, the ionizing radiation is so much reduced that the interstellar hydrogen is un-ionized." Table 3 gives the quantity N_2/N_1+N_2 for several values of the ratio s/s_0.

TABLE 3.—IONIZATION OF HYDROGEN AS A FUNCTION OF DISTANCE

s/s_0	$\frac{N_1}{N_1+N_2}$
0.00	1.00
0.58	1.00
0.74	0.99
0.84	0.98
0.93	0.96
0.97	0.94
1.00	0.85
1.03	0.33

The very rapid decrease of N_2/N_1+N_2 near $s/s_0 = 1$ is of fundamental importance. It shows that each star is surrounded by a sharply limited volume of space where H is almost wholly ionized, while outside of this volume H is un-ionized.

Table 4 gives Strömgren's computations for the radius s_0 of the ionized hydrogen region, as a function of spectral type. The computation is based upon values of the radii corresponding to main-sequence stars.

TABLE 4.—RADII OF REGIONS OF IONIZED HYDROGEN

Spectrum	T	Vis. Abs. Mag.	s_0 in parsecs	s_0 in parsecs for main sequence and $N=3$ cm^{-3}
	°			
O5	79,000	−4.2	$54\times R^{2/3}N^{-2/3}$	67
O6	63,000	−4.1	40	52
O7	50,000	−4.0	29	41
O8	40,000	−3.9	20	31
O9	32,000	−3.6	13	22
B0	25,000	−3.1	7.2	12
B1	23,000	−2.5	5.6	8
B2	20,000	−1.8	4.2	5
B3	18,600	−1.2	3.1	3
B4	17,000	−1.0	2.2	2
B5	15,500	−0.8	1.6	1.8
A0	10,700	+0.9	1.	0.2

The table illustrates the great preponderance of the hot stars in creating volumes of ionized hydrogen. In the regions of ionized hydrogen the Balmer lines will be excited by several mechanisms and will give rise to emission lines. Strömgren identifies these regions with the extended areas of hydrogen emission found in the McDonald Observatory survey of the Milky Way. In these areas O stars are abundant. For a group of n stars the radius s_0 increases as $n^{1/3}$, so that from Table 4 we infer that a group of 10 or 15 late O stars would create an ionized sphere of about 300 parsecs in diameter. This is of same order of size as the observed region in Cygnus (p. 248). In the un-ionized regions nearly all the radiation beyond the Lyman limit, and also that in the Lyman lines L_β, L_γ, etc. has been converted into L_α and low-frequency lines. There will be almost no excitation of the third and higher levels of hydrogen, but the second level may be superexcited by a factor of 10^3.

It is of interest to consider the manner in which the radius of the ionized region depends upon the various quantities involved. In this connection it is important to remember that the discussion applies only to an element which furnishes the vast majority of free electrons. In the ionized regions this is hydrogen, and within these regions the ionization of elements of higher ionization potential is not influenced by a term of the form $e^{-\tau}$. Strömgren derives for s_0, when $T_e = T$:

$$\log_{10} s_0 = -5.85 - \tfrac{1}{3}\log a_\alpha - \tfrac{1}{3}\theta I + \tfrac{1}{2}\log T + \tfrac{2}{3}\log R - \tfrac{2}{3}\log N,$$

where

$$I = \text{ionization potential}, \quad \theta = \frac{5040}{T}, \quad a_\alpha = 6.3 \times 10^{-18}\ \text{cm}^{-2}.$$

But

$$\log R = \frac{5900}{T} - 0.20\, M_v - 0.02.$$

Hence

$$\log_{10} s_0 = -5.85 - \tfrac{1}{3}\log a_\alpha + (3900 - 1660\, I)\frac{1}{T} + \tfrac{1}{2}\log T - 0.13\, M_v - \tfrac{2}{3}\log N.$$

Clearly s_0 is very sensitive to T, because of the term $(3900 - 1660I)$ $1/T$. Except when I is small, $1660\, I/T$ predominates. For example,

when $I = 10$ volts,	$T = 8{,}300$;	$s_0 = 1$
" $I = 10$ "	$T = 16{,}600$	$s_0 = 10$
" $I = 50$ "	$T = 8{,}300$	$s_0 = 1$
" $I = 50$ "	$T = 16{,}600$	$s_0 = 10^5$

The conclusion is that when I is large hot stars alone are important.

The effect of M_v is relatively slight, because of the coefficient 0.13. For a main-sequence star and a supergiant of class A we have

$$\text{main sequence } A0: M = +0.9$$
$$cA0: M = -6.0$$

The value of $\log_{10} s_0$ changes by $0.13 \times 6.9 = 0.9$. If for a main-sequence A0 star Table 4 gives $s_0 = 0.2$ parsec, the supergiant will give $s_0 = 16$ parsecs. This is of the order of size required for α Cygni which may be responsible for the luminosity of the North America nebula and the surrounding emission region. The distance is about 200 parsecs and the apparent radius $s_0 = 4°$. This gives $s_0 = 14$ parsecs, which is close to the value derived from Strömgren's theory.

In the case of γ Cygni, which is of type F8 and which is believed to be responsible for some faint hydrogen emission showing a symmetric arrangement around this star, the agreement is poor. The distance is about 140 parsecs and $s_0 = 4°$. Hence the radius should be $s_0 = 10$ parsecs. But the temperature is much lower than that of α Cygni. It is difficult to see how γ Cygni can be responsible for the emission region unless it radiates at $\lambda 900$ like a late B star. The importance of supergiants may become appreciable in the case of early class B.

Let us next apply the theory to two relatively close O stars, γ Velorum and ζ Puppis. For these stars

$$M_v \approx -4$$

and

$$D \approx 200 \text{ parsecs.}$$

For type O8 Table 4 gives $s_0 = 31$ parsecs. Hence we are well outside the ionized regions surrounding these two stars. Observations confirm this: there is no emission at high galactic latitudes.

EMISSION OF FORBIDDEN OXYGEN

The McDonald Observatory results show the following:

(1) [O II] is nearly always present in the regions of ionized H.

(2) There is a relative strengthening of [O II] in the winter Milky Way and a weakening in the summer Milky Way.

(3) The regions of [O II] coincide with those of H and have the same sharp boundaries.

(4) [O III] is rarely observed, but when it does occur it is limited to the inner parts of the H regions, and it shows no sharp boundaries.

(5) [O I] was never observed, although a special effort was made to distinguish it from the strong auroral lines in the spectrum of the night sky.

These results are in good agreement with Strömgren's theory. Since N_e depends on H, the decrease of [O III]-intensity is caused by the term $1/s^2$. The same is true for [O II]; at the boundary of H the ionization of O will also suddenly stop. Since all exciting stellar radiation is cut off at s_0, elements of ionization potential higher than that of H, 13.54 volts, are un-ionized. This applies to the following:

O	I.P. = 13.56 volts
O^+	34.94
O^{++}	54.88
He	24.48
C^+	24.28
N	14.49

Elements of lower ionization potential may be ionized in the regions where H is neutral. This applies to

C	I.P. = 11.22 volts
Ca	6.09
Ca^+	11.82
Na	5.11

Carbon is probably the most abundant of these elements and it must be the source of the free electrons in these regions. Allowing for the low abundance of C with respect to H, we estimate that in the nonhydrogen regions N_e is between 10^{-2} and 10^{-3} cm^{-3}. It will be recalled that this is very similar to the value originally inferred by Gerasimovič and Struve for interstellar space. Hence conditions of ionization for Ca and Na in the nonhydrogen regions must be approximately those which they had derived. This means that Ca is nearly all doubly ionized, so that if we observe a star through a series of hydrogen and nonhydrogen regions, it is the former that give most of the absorption within the stationary lines of Ca II.

Na I is even more reduced in the nonhydrogen regions and Ca I originates almost entirely in the regions of ionized hydrogen.

It is not at once obvious why [O I] is not observed outside the regions of ionized hydrogen. It is certainly not ionized, because the ionization potential of O almost coincides with that of H. The forbidden lines of [O I] are also weak in planetaries. There we could make the plausible assumption that the gas ceases to exist in the ring in which we should otherwise expect [O I] to be strong. But this does not help in the case of interstellar space. Provisionally it seems possible that because of the low electron density in the nonhydrogen

regions there are not enough collisions to excite the metastable levels of O I. Since the high levels are probably not appreciably excited by radiation and since there is no ionization, recombination and cascading can not help to populate the metastable levels. We are compelled to assume that excitations by electron collisions are not sufficiently numerous to produce the forbidden lines.

It is of some interest to compute the abundance of O from the observed intensities of the line λ3727. The observational data give us n_2, the number of atoms per cm² in the upper, metastable level:

$$\log n_2 = 11.97.$$

This is very large compared to hydrogen, because of the metastability of the term. We can now apply two methods of reasoning in order to determine n_1: (1) excitation by pure radiation and (2) excitation by collisions.

Method (1) depends upon the formula for the three-state problem, with the second level assumed to be metastable:

$$\frac{n_2}{n_1} = W \frac{A_{32}}{2A_{21}} \rho_{13}$$

where

$$\rho_{13} = e^{-(h\nu_{13}/kT)}.$$

Using $T = 25{,}000°$, $W = 10^{-17}$we have $\rho_{13} = 10^{-4}$. Since $A_{32} = 10^8$ sec^{-1}; $A_{21} = 2.4 \times 10^{-5}$ sec^{-1}, we have

$$n_2/n_1 = 2 \times 10^{-9}.$$

$$n_1 = 5 \times 10^{20}.$$

If $s_0 = 300$ parsecs $= 10^{21}$ cm, we find

$$N_1 \approx 10^{-1} \text{ cm}^{-3}.$$

Since nearly all O is ionized we infer that

$$N(O) = 10^{-1} \text{ cm}^{-3}.$$

Method (2) makes use of the equation

$$\frac{n_2}{n_1} = \frac{N_e a_{21}}{A_{21} + N_e a_{21}} e^{-(h\nu/kT)},$$

where a_{21} is the collisional probability:

$$a_{21} = \sigma^2 2 \left(\frac{2\pi kT}{m}\right)^{1/2} = 3 \times 10^{-10}$$

For the low metastable level

$$e^{-(h\nu/kT)} = 0.4.$$

If we assume $N_e = 1$ cm^{-3}, we get approximately

$$\frac{n_2}{n_1} = \frac{N_2}{N_1} = 5 \times 10^{-6}.$$

Since $n_2 = 10^{12}$ we find

$$n_1 = 2 \times 10^{17}.$$

Adopting again $s_0 = 10^{21}$ cm, we have

$$N_1 = 2 \times 10^{-4}.$$

Evidently, the collisional mechanism is much more efficient than the radiation mechanism. The abundance of O may be somewhere between the two limits. Strömgren has independently estimated from the same observational data that the interstellar abundance of oxygen is 10^{-2} or 10^{-3} atoms to one atom of hydrogen. The method upon which these computations are based is very rough, but as a preliminary result we shall adopt

$$N(O) = 10^{-3} \text{ cm}^{-3}.$$

The heterogeneity of the Milky Way in regard to the relative intensities of [O II] and H leads to interesting speculations. It may be due to real differences in abundance. But it may also be due to different conditions of excitation.

INTERSTELLAR EMISSION OR ABSORPTION

In the past astronomers have sometimes been searching for interstellar emission lines of Ca II and Na I, and it is of some interest to explain why these lines are observed in absorption, while H is observed in emission. Let us compare the emission of H and Ca II. From the absorption intensities we know that

$$N_2(\text{Ca}^+) = 10^{-8} \text{ cm}^{-3}.$$

The total emissions in H_α and Ca K are

$$4\pi E_\alpha = n_3 h\nu_{32} A_{32} \text{ for H}$$
$$4\pi E_K = n_K h\nu_K A_K \text{ for Ca}^+$$

Since we are only concerned here with orders of magnitude we may put

$$h\nu_{32} = h\nu_K$$

$$A_{32} = A_K$$

Accordingly,

$$\frac{E_a}{E_K} = \frac{n_3}{n_K} = \frac{5}{n_K},$$

because $n_3 = 5$ cm^{-3} (page 248). But

$$n_K = 10^{-8} \times 10^{21} \times W \frac{g_K}{g_1} e^{-(h\nu/kT)}.$$

For $T = 15{,}000°$ and $W = 10^{-16}$,

$$\frac{E_a}{E_K} \approx 10^3 \text{ or } 10^4,$$

so that the emission of Ca K can not be observed.

In a similar manner we can show that no interstellar absorption lines of H are expected in the spectra of distant stars, for example in a Nova which provides an emission background on which an interstellar line could easily be seen. The absence of any such line in Nova Lacertae, at a distance of about 900 parsecs, shows that

$$n_2 < 10^{12} \text{ cm}^{-3},$$

because if it were stronger our spectrograms would show it. We also know that for the third level, which is not metastable,

$$n_3 = n_1 W e^{-(h\nu_{31}/kT)} = 5,$$

while for the second, which is metastable:

$$n_2 = n_1 W \frac{A_{31}}{A_{21}} e^{-(h\nu_{32}/kT)},$$

Since $A_{31} = 10^8$ sec $^{-1}$ the inequality becomes

$$\frac{1}{A_{21}} = \tau_2 < 2 \times 10^3 \text{ sec.}$$

The question arises whether this is in accord with the theory. Breit and Teller find that in the absence of collisions the mean life of the $2s$ state of hydrogen is about 1/7 second. Hence the Balmer absorption lines should not be observable.

COMPOSITION OF INTERSTELLAR GAS

Table 5 summarizes the results. I have combined the results of Dunham and Strömgren with my own, without making an attempt to avoid slight inconsistencies. In my opinion the theory, as well as the observations, permits only a very rough orientation. In Dunham's work the atoms refer to the space between the earth and χ^2 Orionis; those for the molecules represent the means for several stars.

TABLE 5.—COMPOSITION OF INTERSTELLAR GAS
LOGARITHMS OF NUMBERS OF PARTICLES PER CM³

Element	This paper	Dunham	Sun	Nebulae
Electrons	0.2	1		
Hydrogen	0.2	1	0	0
Oxygen	−3		−1.5	−2
Sodium	−6	−4	−3.3	−4
Potassium		−5	−3.7	−5
Calcium	−7	−5	−3.8	−4
Titanium		−7	−5.3	−4
CH		−6		
CN		−6		

For comparison the table gives also the relative abundances in the sun from Russell and in the nebula NGC 7027 from Bowen and Wyse. These values were adjusted for one hydrogen atom. The discrepancies between the results of this paper and Dunham for Ca and Na are attributable to differences between the determinations of Dunham and of Merrill, Wilson, and Sanford. However, there are real differences in different parts of the sky. Dunham found for the neighborhood of the sun a density of 10^{-10} Ca ions per cm³; for the space between the earth and χ^2 Orionis he finds 10^{-7}, while Merrill and Sanford find 10^{-8} for the average of many stars. There are also serious difficulties with the curve of growth for interstellar absorption lines. Accordingly, we need feel no concern about the differences. It seems that the composition of the gas is similar to that of the sun and of the nebulae.

It seems to me that the most important task now is to study in detail the heterogeneity of the galaxy. We have definite observational indications that the relative intensities of different atoms are different in various parts of the sky. It is surprising, for example, that some of the newer interstellar lines are strong in ζ Ophiuchi. Adams has shown that λ 4232.6 and CH 4300.3 are relatively strong in this star. But Ca K is not particularly strong. The star is of very early B type (Morgan finds it may even be an O) and probably creates a moderate volume of ionized H. But it lies quite far from the Milky Way and from other O stars. The data now available are not sufficient for a

detailed study, and we can only give a few hints as to the topics such a study might cover:

(1) The relative weakness of K and the strength of molecular lines in ζ Ophiuchi, far from the other O-type stars and from the Milky Way, suggest that the ionized volume is small and that molecular lines are strengthened in the un-ionized regions. We have as yet no accurate theory of the equilibrium of CH and NH and it is difficult to predict the outcome. Swings has made some computations and has shown that certain diatomic molecules, like CH and NH, must be quite frequent. The ionization of H may well impede the formation of the molecules, and it is quite possible that they will be relatively more numerous in the un-ionized regions.

(2) Adams states that Ca I 4227 does not appear in ζ Ophiuchi. This agrees with the prediction of Strömgren's theory (page 249) for a relatively un-ionized region. This is also true of the correlation between Ca I and Ca II, noticed by Adams.

(3) Because of the fact that interstellar Ca II and Na I originate principally in the ionized H regions, we should expect that there would be appreciable departures from the simple one-half relation in the galactic rotation term, which was discovered by Oort, and confirmed by Struve and by Plaskett and Pearce. However, since the regions are large it is important that the comparison of radial velocities be confined to those stars and their Ca II lines which are principally responsible for the creation of a volume of ionized H.

(4) In order to aid in the study of the heterogeneity of the galaxy, more material is required with the nebular spectrographs.

(5) An application of Strömgren's theory to diffuse gaseous nebulae, such as the Orion nebula, and to planetaries, should be made, with special attention to the theoretical and observational study of absorption lines, such as the lines of He I discovered by O. C. Wilson.

(6) A regional study of interstellar Ti II should be relatively easy. From the theory we should expect a behavior which is essentially similar to that of Ca II and Na I.

(7) The observational problem of determining N_3 for interstellar H has not been solved with sufficient precision.

(8) A study of the effects of stellar lines in early B stars and the determination of good spectroscopic parallaxes for these stars will improve our knowledge of N_2 (Ca^+) and N_1 (Na).

(9) The nature of the contours of the interstellar lines must be cleared up by extending the determination of line contours to very distant stars located near the nodes and near the maxima or minima of the curve of galactic rotation as a function of galactic longitude.

PALEONTOLOGY.—*New Middle Devonian stratigraphic names.*[1] G. ARTHUR COOPER, U. S. National Museum, and ALDRED S. WARTHIN, Vassar College.

These new names are proposed to make them available for use on the "Devonian Correlation Chart" of the National Research Council.

Stone Mill member of the Ludlowville formation: A thin bed of limestone varying from 1 to 3 feet in thickness and exposed at several localities on both sides of Chenango Valley in Morrisville Quadrangle, east-central New York. The type section is located in the bed and banks of Stone Mill Brook, 4½ miles (airline) southeast of Lebanon and about 1½ miles northwest of Earlville, N. Y. The layer has only a local distribution but as the easternmost representative of the Centerfield limestone has considerable stratigraphic significance. It consists mostly of crinoidal and fragmentary shell material but contains considerable sand. Its westernmost exposure is in a small glen at the southeastern tip of Bradley Brook Reservoir, and its easternmost appearance is in a ravine about 2½ miles southwest of Poolville. This member contains a fairly large fauna the most important species of which are: *Prismatophyllum* n.sp., *"Spirifer" venustus* Hall, *Vitulina pustulosa* Hall, *"Sp." sculptilis* Hall, and many water-worn corals.

The Stone Mill member represents the last detected appearance of the Centerfield formation in eastern New York. The overlying fine-grained sandstone also contains many elements of the Centerfield fauna but it has not proved possible to trace them beyond the eastern limit of the Morrisville Quadrangle. It is therefore thought that the crinoidal and shell debris, together with the rolled corals, represents an eastern-shore phase of the Centerfield.

Logansport limestone: The name of this formation is derived from the city of Logansport, north-central Indiana, but the exposure selected as the type section is located at Pipe Creek Falls, 2 miles above the junction of Pipe Creek and the Wabash River, 7 miles above Logansport. Here 12 feet of light-colored granular limestone overlies the Silurian at the falls; corals and other fossils are abundant particularly in the upper 6 feet. Important Centerfield elements in the fauna are: *Camarospira, Eunella attenuata, Camerophoria, Cyclorhina,* and *"Spirifer" venustus.*

This formation had previously been correlated with the Onondaga limestone on the basis of the reported presence of *Spirifer acuminatus* and other Onondaga types. This confusion of Onondaga and Hamilton types occurred because the Logansport formation has a "reef facies"

[1] Published by permission of the Secretary of the Smithsonian Institution. Received February 21, 1941.

like parts of the Onondaga. Re-examination of the fossils shows closest affinities of the Logansport to the Four Mile Dam limestone of the Traverse Group of Michigan.

Hungry Hollow formation: Proposed for the Encrinal limestone and coral bed at the base of the Widder formation in southwestern Ontario. These two beds contain a fauna wholly unlike that of the Widder. Although the Encrinal and coral bed are unlike in lithology the two contain the same fossils and are thus a faunal unit. The type section is in the bluffs along the Aux Sables River in Hungry Hollow (also known as Bartlett's or Marsh's Mill), 2½ miles east of Arkona, Ontario. Here the Hungry Hollow formation consists of 2½ feet of light-brown crinoidal limestone overlain by 3 to 4 feet of calcareous shale abounding in corals and other fossils. The formation contains an almost exact duplication of the Centerfield fauna of western New York.

Four Mile Dam limestone: Type section located at the Four Mile Dam on Thunder Bay River, Alpena County, Mich. The rock exposed at this place is a part of a reef of uncertain thickness overlain unconformably by the Norway Point formation. The Four Mile Dam limestone abounds in fossils of Centerfield affinities: *"Spirifer" venustus, Camarospira, Camerophoria, Cyclorhina, Parazyga,* and *Strombodes alpenensis.*

Newton Creek limestone: Proposed for the brown, bituminous and crystalline limestone 25 feet thick exposed 12 feet above the floor of the Michigan Alkali Company Quarry, Alpena, Mich., and extending to a thin black shale at the base of the Alpena limestone. The formation abounds in large brachiopods: *Cranaena, Pentamerella, Camerophoria,* and *Charionella.*

Rockport Quarry limestone: Proposed to replace Rockport limestone of Smith, 1916 (not Bastin, 1908; Krebs, 1911; or Marbut, 1904). The type section is in the quarry of the Kelly Island Rock and Transport Company at Rockport in the northeast corner of Alpena County, Mich.

BOTANY.—*Elongation of mesocotyls and internodes in Job's-tears* (Coix lachryma-jobi *L.*).[1] JAMES H. KEMPTON, U. S. Bureau of Plant Industry.

Numerous experiments with maize seedlings grown in the dark have shown that the elongation of the mesocotyl (epicotyl) ceases with the exsertion from the coleoptile of the first leaf. It has been established also that 100 F.C. hours Mazda illumination at approximately 26° C., when the seedlings are 2 to 5 cm tall, result in a reduction in the final length of the mesocotyl of approximately 25 to 30 percent. When the mesocotyl has attained the length maximum for the seed stock and the experimental conditions, further elongation of the seedling takes place in the first internode—the internode between the coleoptile and the first leaf.

Seedlings of the Asiatic maize relative, *Coix lachryma-jobi* L., differ morphologically from those of maize in having a bladeless sheath interposed between the coleoptile and the first true leaf. It was of interest, therefore, to determine for *Coix* whether cessation of elongation of the mesocotyl awaited the appearance of the first true leaf or followed upon the exsertion of the bladeless sheath.

Coix is native to the Oriental humid tropics of very heavy rainfall and may be considered at least semiaquatic in habitat. Importation of seed from the Orient is proscribed because of the prevalence there of a mildew capable of attacking maize. However, the hard-shelled forms have been grown in this country for years as a source of beads, and a stock of this seed was obtained from the W. Atlee Burpee Co.

Preliminary experiments showed that the seedlings of this stock, when grown in the dark, produced mesocotyls almost twice the length of those of the Funk Yellow Dent used in maize experiments. Mesocotyls as long as 450 mm were obtained, and this length at least equals that found in the desert maize of the Hopi Indians.[2] In the case of the Hopi maize, long mesocotyls are an evident adaptation to the deep planting required to place the seed in moist soil, whereas in *Coix* they may be considered as a useful adaptation for an aquatic habitat where the seeds may be buried along stream banks.

The experiments with *Coix* indicated that, with the exsertion of the bladeless sheath from the coleoptile, the elongation of the mesocotyl ceased. However, it developed that upon the cessation of elongation of the mesocotyl further elongation of the seedling took place at

[1] Received March 25, 1941.

[2] COLLINS, G. N. *A drought-resisting adaptation in seedlings of Hopi maize.* Journ. Agr. Res. 1: 293–301, illus. Jan. 10, 1914.

the second internode instead of the first as in maize. The first internode was not extended and the coleoptile and bladeless sheath remained essentially paired as almost opposite organs (Fig. 1).

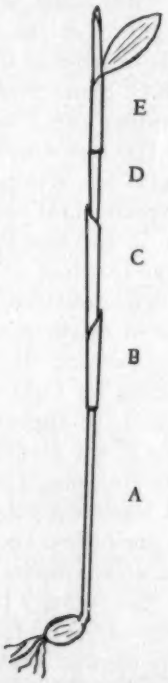


Fig. 1.—Diagrammatic representation of *Coix* seedlings: (A) Mesocotyl, this organ may elongate 450 mm; (B) coleoptile; (C) bladeless sheath, the node bearing this sheath is not shown but is within 1 or 2 mm of the node at the base of the coleoptile; (D) second internode; (E) first true leaf.

A number of experiments have been conducted, all giving the same results. When the mesocotyl is checked, the second internode elongates. A single experiment is presented in Table 1 where one-half of a flat of seedlings growing in the dark was given an exposure of 100 F.C. hours Mazda illumination, the other half remaining in the dark.

From the measurements it is evident that the illumination given one-half the seedlings resulted in a very great reduction in the elongation of mesocotyls and stimulated the elongation of second internodes. No effect of illumination is found in the coleoptiles, though a similar treatment of maize would have measurably increased the length of the coleoptiles. The bladeless sheaths, however, definitely responded

TABLE 1.—LENGTHS OF VARIOUS PARTS OF SEEDLINGS OF COIX LACHRYMA-JOBI L., HALF OF WHICH WERE GROWN WHOLLY IN THE DARK, THE OTHER HALF SUBJECTED TO A SINGLE EXPOSURE OF 100 F.C. HOURS MAZDA ILLUMINATION WHEN 2 TO 5 CM TALL.

Character	Light exposure		Difference
	Dark throughout	100 F.C. hours	
	Mm	*Mm*	*Mm*
Mesocotyl	253.71 ± 8.94	133.41 ± 7.90	120.30 ± 11.93
Coleoptile	30.32 ± 1.33	30.27 ± 1.11	.05 ± 1.74
First sheath	40.87 ± 1.41	56.30 ± 1.75	15.43 ± 2.25
Second internode	— —	54.19 ± 3.78	— —
First true leaf	82.56 ± 6.33	144.96 ± 6.71	62.40 ± 9.22

to the brief illumination. Evidently the mesocotyl of *Coix* is much more sensitive to light than is the maize mesocotyl, although this has not been tested beyond the reduction in length effected by 100 F.C. hours. In maize it has been possible to detect the effect of 1,000 F.C. seconds, and it would appear to be possible with *Coix* to measure the response to even smaller amounts of light.

The failure of *Coix* to elongate the internode between the coleoptile and the bladeless sheath is suggestive that this sheath and the coleoptile are more intimately related in function than is the case with maize. The greater sensitivity of *Coix* to light, as compared with maize, and the extensive elongation of *Coix* mesocotyls, together with the close physical association of the coleoptile and bladeless sheath, suggests that both these latter organs produce the growth substance required for mesocotyl elongation.

ZOOLOGY.—*Ostracoda from Puerto Rican bromeliads.*[1] WILLIS L. TRESSLER, University of Maryland. (Communicated by WALDO L. SCHMITT.)

It has been about 60 years since the first discovery of Entomostraca in the leaf cups of bromeliads in southern Brazil. Since then this habitat has been investigated in several places, and a long list of animal forms has been assembled, many of which are found almost exclusively in this peculiar situation.

The bromeliads are large tropical plants built on the lines of a century plant or the pineapple, which is a member of this group. The leaves, which may be several feet in length, are arranged in a spiral fashion with overlapping bases, which form little cups in which rain water collects. Bromeliads are mainly epiphytic on the large trees of tropical America but are found also in most botanical gardens of

[1] Received March 12, 1941.

temperate regions where they thrive under glass. The cups at the leaf bases are filled with decomposing debris and water, and in the water or among the debris or attached to the sides of the leaves are to be found a great variety of organisms, including copepods, ostracods, and worms.

The first report on Entomostraca inhabiting the leaf cups of bromeliads was made by Fritz Müller in 1880 (Müller, 1880) and concerned the discovery of various microscopic animals that he had found in these reservoirs in southern Brazil. Included was a new species of ostracod, which was described the following year (Müller, 1881). More recently, Picado (1913) in his masterly study of the organisms to be found in the leaf cups of bromeliads, recorded about 250 species of animals that have been found in this habitat in various parts of the world. This list of species includes representatives from such groups as the rotifers, oligochaete worms, leeches, planarians, ostracods, copepods, isopods, Onychophora, Myriapoda, Acarina, Phalangida, Pseudoscorpionida, scorpions, spiders, gastropods, insects, and amphibians. Of these, the insects were by far the most largely represented.

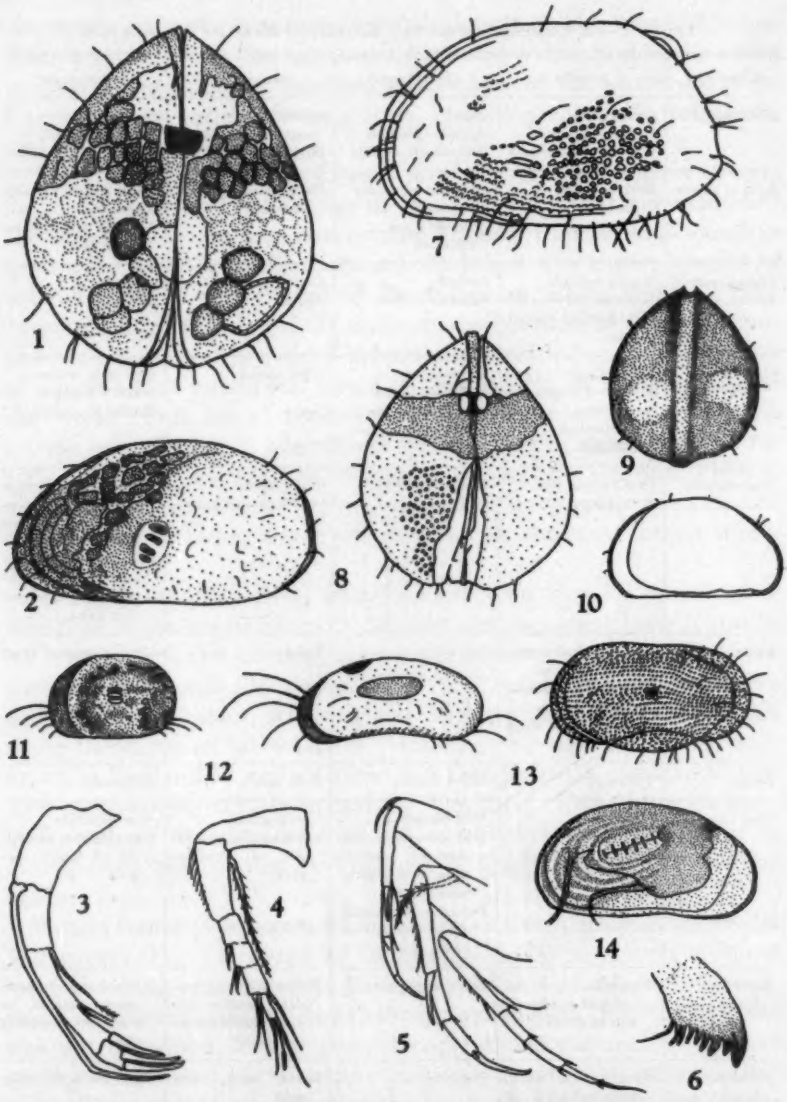
In Brazil, Müller (1881) found an ostracod that he described as *Elpidium bromeliarum* (Figs. 9, 10) but that has since been found to be a species of the already discovered genus *Metacypris*. Only one species of this genus (*M. cordata*, Figs. 7, 8) was known from northern Europe and Hungary, where it was an inhabitant of shallow water along the shores of lakes (G. W. Müller, 1900). It was subsequently found in England as well. A variety of the European species (*M. cordata neocomensis*) was described by Thiebaud (1906) from Switzerland, and an American species (*M. americana*, Fig. 13) by Furtos (1936) from the cenotes of Yucatan. A fourth species is described herein.

Picado found two genera of ostracods in Costa Rica: A species of *Metacypris* (Fig. 11) found at La Mica at 1,500 meters elevation, a form that was considered to be closely related to *M. bromeliarum*, and a species that was referred to the genus *Candona* (Fig. 12) but that was not described. In the present paper the occurrence of another species of ostracod (*Candonopsis kingsleyi*) is recorded from the leaf cups of bromeliads, which brings the total number of ostracod species found in this habitat to three, or perhaps four if Picado's *Metacypris* can be considered a distinct species.

Ostracoda and Entomostraca in general have been found in many strange and unexpected places, the leaf cups of bromeliads being only

TABLE 1.—A COMPARISON OF THE KNOWN SPECIES OF METACYPRIS

Character	*cordata*	*bromeliarum*	*americana*	*maricaoensis*
Shell-profile	Ovoid Height = ⅔ length Highest = posterior ⅓	Ovoid Height = ⅔ length Highest = in middle	Ovoid Height = ⅔ length Highest = in middle	Ovoid Height = ⅔ length Highest = in middle
Ends of valves	Both broadly rounded	Posterior = broadly rounded Anterior = less rounded	Both broadly rounded	Posterior end broadly rounded Anterior end not so much so
Dorsal margin Ventral margin	Nearly straight Sinuated but covered in part by bellied sides	Arched Same as *cordata*	Gently arched Same	Arched Same
Shell-dorsal view	Very tumid Width = ⅔ length Anterior end pointed Posterior end rounded	Very tumid Width = ⅔ length Anterior end less pointed than *cordata*	Very tumid — Same	Similar to *cordata* Width = ⅔ length Similar to *cordata*
Shell-surface	Small round pits Strong hairs	Smooth, no pits Few hairs	Pits present Few long stiff hairs	No pits, covered with a pattern of polygonal areas in anterior half Broad band of polygonal areas over dorsal shell margin. Few hairs.
Color	Posterior half = dark grayish brown Greenish mixture in middle Broad light band dorsal border	Not given	Gray	Gray, polygonal areas brown
Length	0.56 mm	1.2–1.3 mm	0.55 mm	0.78 mm
First antenna	Slender Six segments Spine on second segment poorly developed	Five segments Dorsal border of first segment terminates in a thickly haired wart Spine reaches to middle of fourth segment	Five segments Spine reaches to middle of terminal claw	Five segments Spine reaches to middle of fourth segment
Second antenna	Exopodite well developed, reaches to tips of claws	Same as *cordata*	Exopodite long, slender, reaches beyond tips of terminal claws	Exopodite well developed, reaches to tips of terminal claws
Mandibular teeth	Four to five teeth, each with 2 or more points	Seven teeth	Seven teeth, each split	Eight teeth, not split
Thoracic legs	Broad at base	Similar	Similar	Similar to others



Figs. 1–6.—*Metacypris maricaoensis*, n. sp.: 1, Dorsal view, female; 2, left valve, female; 3, second antenna, female; 4, first antenna, female; 5, thoracic legs, female; 6, mandibular teeth, female. Figs. 7–8.—*Metacypris cordata* G. W. Müller: 7, Left valve, female; 8, dorsal view, female. Figs. 9–10.—*Metacypris bromeliarum* (Fr. Müller): 9, Dorsal view, female; 10, left valve, viewed from within, female. Fig. 11.—*Metacypris* sp. (from Costa Rica). Fig. 12.—*Candona* sp. (from Costa Rica). Fig. 13.—*Metacypris americana* Furtos, right valve, female. Fig. 14.—*Candonopsis kingsleyi* Brady and Robertson, lateral view, male. (Figs. 7–8, after G. W. Müller; 9–10, after Fr. Müller; 11–12, after Picado; 13, after Furtos.)

one of the many peculiar habitats that these creatures select for their life abode. Some species have been found only in these strange places, a fact clearly brought out in an interesting recent paper by Scourfield (1938).

The material reported upon in the present paper was sent to the author for identification by Dr. Waldo L. Schmitt, curator of marine invertebrates, U. S. National Museum. The collections had been made in the Maricao National Forest in Puerto Rico in 1936 and 1937 by Prof. George S. Tullock, of Brooklyn College, and Prof. W. A. Hoffman, of the Columbia School of Tropical Medicine, San Juan.

The slides of the dissected ostracods and the specimens in alcohol have been desposited in the U. S. National Museum as type specimens.

Suborder PODOCOPA

Family CYPRIDAE: Subfamily CYPRINAE

Genus **Candonopsis** Vavra, 1891

Laterally compressed forms with thin shells. Anterior antennae, slender; posterior antennae, with penultimate joint subdivided, natatory setae poorly developed. Mandibular palp long and slender with a much-produced terminal joint. Maxillipeds with a vibratory plate bearing three thick, plumose setae; palp in male transformed as in *Candona* into a prehensile organ. Dorsal margin of furca without setae.

This genus includes one species found in Europe and several from the Southern Hemisphere.

Candonopsis kingsleyi (Brady and Robertson) Fig. 14

Candona kingsleyi (part) Brady and Robertson, Ann. Mag. Nat. Hist. (ser. 4) **6**: 17, pl. figs. 11, 12. 1870.
Candonopsis kingsleyi Vavra, Sitzber. Böhm Ges., 1891, p. 162.
Candonopsis kingsleyi Müller, Zool. **30**: 38, pl. 6, figs. 6, 7, 23–28; pl. 7, figs. 22, 25. 1900.

Specific characters.—Female: Seen from the side, reniform with rounded ends, highest a little posterior to the middle. Posterior end slightly more broadly rounded than the anterior end. Dorsal margin forming an evenly rounded curve; ventral margin slightly concave. From above, very narrow with greatest width slightly behind the middle; anterior end somewhat more pointed than the posterior. Valves with very smooth shiny surfaces and with a few fine hairs. Inner duplicatures very broad, particularly at the anterior end where the inner edge forms an almost vertical line. Anterior antennae long and slender; posterior antennae also slender. Mandibular palp with terminal joint narrowly produced and of about the same length as the preceding joint. Maxillipeds with tapering palp exhibiting a very small terminal joint. Second pair of legs with the two shorter bristles of unequal length, the shorter being less than one half the length of the other. Furcal rami very narrow and slightly curved, without dorsal seta; claws without strong teeth.

Male, somewhat larger than the female. Prehensile palps of maxillipeds

short and thick and slightly unequal, the right being broader. Copulatory appendages terminate in two unequal lappets, the upper one being larger and of triangular shape. Ejaculatory tubes are very large and conspicuous and are distinctly visible through the transparent shell. Color whitish, translucent. Length of male, 1.06 mm; height, 0.54 mm; width, ca. 0.20 mm. Female slightly smaller.

Occurrence.—From bromeliads, Maricao National Forest, Puerto Rico, 2,800–3,000 feet elevation, December 1937.

Distribution.—Sweden, British Isles, Germany, Bohemia, Switzerland, Siberia.

Family CYTHERIDAE

Genus **Metacypris** Brady and Robertson, 1870

Metacypris Brady and Robertson, Ann. Mag. Nat. Hist. (ser. 4) **6**: 19. 1870.
Elpidium F. Müller, Arch. Mus. Nac. Rio de Janeiro **4**: 27. 1881.
Metacypris G. W. Müller, Zool. **30**: 95, pl. 21, figs. 1–9. 1900.
Metacypris Thiebaud, Zool. Anz. **29**: 799. 1906.
Metacypris Furtos, Carnegie Inst. Washington Publ. **457**: 114, figs. 31, 32, 44–46. 1936.

Very short broad shells; right valve with toothed anterior and posterior margins. First antennae with five or six segments. Second antennae, four segmented, the exopodite jointed. Mandibles with obscurely segmented palp. Maxilla with three masticatory processes and a shorter palp; branchial plate without aberrant or orally directed setae. Furca of female with three setae.

Metacypris maricaoensis, n. sp. Figs. 1–6

Specific characters.—Female: From the side, oval in outline with greatest height at about the center. Dorsal margin broadly arched, ventral margin almost straight. Both ends rounded, the posterior end being more broadly rounded than the anterior, which shows a pronounced slope from the dorsal margin. Seen from above, very tumid with broadly rounded posterior and more tapered anterior ends. Large fused eyes very prominent. Valves smooth with a few scattered, strong hairs. Color, gray with a much darker area in the anterior half of the valve which consists of a band of polygonal shaped, dark brown areas across the two valves at the region of the eyes. First antenna with five segments, the spine on the second segment well developed and reaching to the middle of the fourth segment. Second antenna with well developed exopodite which reaches to the tips of the terminal claws. Mandible with eight teeth which show no evidence of being split. Thoracic legs broad at the base and in other respects similar to those of other members of the genus.

Length of adult female, 0.78 mm; height, 0.39 mm; width, 0.64 mm.

Male unknown.

Occurrence.—Numerous specimens were taken from leaf cups of bromeliads in the Maricao National Forest, Puerto Rico, at an elevation of 2,800–3,000 feet, January 28, 1936, and December 1937. Female holotype, U.S.N.M. no. 80029.

Remarks.—This species is evidently closely related to *M. cordata* but differs from it in several important respects, viz. the greater size, shape of the shell and the color markings, the absence of pits on the valves, and the marked difference in the mandibular teeth.

LITERATURE CITED

FURTOS, N. C. *On the Ostracoda from the cenotes of Yucatan and vicinity.* Carnegie Inst. Washington Publ. **457**: 89–115. 1936.

MÜLLER, F. *Wasserthiere in Baumwipfeln.* Kosmos **6**: 386–388. 1880.

———. *Descripção do Elpidium bromeliarum.* Arch. Mus. Nac. Rio de Janeiro **4**: 27–34. 1881.

MÜLLER, G. W. *Deutschlands süsswasser ostracoden.* Zool. **30**: 1–112. 1900.

PICADO, M. C. *Les bromeliaces epiphytes considerees comme milieu biologique.* Bull. Scient. France Belgique (7) **47**: 215–360. 1913.

SCOURFIELD, D. J. *Entomostraca in strange places.* Journ. Quekett Micr. Club (ser. 4) **1**(3): 116–122. 1939.

THIEBAUD, M. *Sur la faune invertébrée du lac de St. Blaise.* Zool. Anz. **29**: 795–801. 1906.

ICHTHYOLOGY.—Kraemeria bryani, *a new species of trichonotid fish from the Hawaiian Islands.*[1] LEONARD P. SCHULTZ, U. S. National Museum.

The reference of genera of fishes to the family Trichonotidae by various authors from time to time has frequently been the result of inadequate material for comparison of their anatomical characters. The genera centering around *Kraemeria* have features that resemble the trichonotids more than the gobiids, and this has influenced me to place them in a subfamily. However, *Paragobioides* Kendall and Goldsborough has been referred to this group by Fowler, but it certainly does not resemble any of the trichonotids except by its elongated body and numerous fin rays. Some pores over the eye, no lateral line, and the restricted gill opening cause me to conclude that *Paragobioides* is nearer the Gobiidae than the Trichonotidae. Its true relationship will be determined no doubt from a study of its skeleton, and until that is done I propose to consider it tentatively as a distinct subfamily. Thus I am inclined to believe that Hora (Rec. Indian Mus. **27** (pt. 6): 455. 1925) in referring *Paragobioides* to the subfamily Taenioidinae under the Gobiidae is close to the true relationship of this species.

In order to separate the various genera referred to the family at various times (from a practical viewpoint) and to indicate some of the relationships between Hawaiian, Samoan, and Phoenix Island material, I have prepared a key and incorporated the various genera as noticed by me in the literature.

1*a*. Lateral line present, below the midaxis at least posteriorly; lower jaw shortest, snout projecting in front of the thin and weak lower jaw; tip of tongue free, narrow and pointed, not bilobed; gill membranes extending far forward, free from isthmus (LIMNICHTHYINAE).

[1] Published by permission of the Secretary of the Smithsonian Institution. Received March 25, 1941.

2*a*. Lateral line along midaxis anteriorly, below it posteriorly, meeting or nearly meeting its fellow behind the anal fin; snout much projecting in front of lower jaw, tip of snout fleshy, protractile; lips of lower jaw with cirri on sides.

3*a*. Sides of body fully scaled; pelvic rays I, 5; dorsal fin rays fewer than 30; fewer than 45 scales in lateral line.

4*a*. Dorsal fin rays about 25 or 26; anal 27 to 29; pectoral 13, the lower rays not separated and different from upper rays; scales in lateral line about 40 ..... *Limnichthys*[2] Waite

4*b*. Dorsal rays 19; anal 29; pectoral 8+9=17, lower rays longer than and somewhat separated from upper rays; scales in lateral line 37 ..... *Schizochirus*[3] Waite

2*b*. Lateral line below midaxis anteriorly, abruptly decurved behind pectoral fin, then continuing about halfway from midaxis to base of anal fin along lower side but not meeting its fellow behind anal fin; snout a little longer than lower jaw and somewhat fleshy; dorsal origin behind that of anal, over third to fourth anal ray; dorsal rays 35; anal 42; pectoral 15; pelvics I, 5 . . . *Tewara*[4] Griffin

3*b*. Sides of body not fully scaled, naked at least above and below lateral line anteriorly; dorsal fin rays more than 30; about 53 to 60 pores and scales in lateral line; dorsal rays 37 or 38; anal 35 to 37; pores in lateral line 54; pelvic rays I, 5; the only scales present occur along lateral line ..... *Crystallodytes cookei*[5] Fowler

1*b*. Lateral line present or absent; if present its course is along midaxis and not below it; snout either shorter than lower jaw (the latter strongly projecting) or lower and upper jaws about same length.

5*a*. Body naked; gill membranes narrowly attached to isthmus free for some distance forward; tongue bilobed; dorsal rays about 19 or 20, about first 5 simple; anal about 13 to 15, the first ray probably simple; pelvics I, 5; inner rays longest; about 9 or 10 branched rays in caudal fin (KRAEMERINAE).

6*a*. Pectoral rays 3 to 5; dorsal rays 19 or 20; anal 12 to 14, rarely 15. *Kraemeria bryani*, n. sp.

6*b*. Pectoral rays 7 or 8; dorsal rays 19 or 20; anal usually 14 or 15. *Kraemeria samoensis* Steindachner

5*b*. Body fully scaled, although scales may be minute on *Paragobioides*, in which case dorsal rays about 60; tongue not bilobed but rounded or pointed.

7*a*. Gill membranes not widely joined to isthmus but free forward, gill opening not restricted to sides (TRICHONOTINAE).

8*a*. First one or two anterior rays of dorsal long and filamentous; inner rays of pelvics long and filamentous *Trichonotus*[6] Block in Schneider; *Taeniolabrus*[6] Steindachner

[2] *Limnichthys* Waite, Rec. Australian Mus. 5(pt. 3): 178. 1904 (genotype, *Limnichthys fasciatus* Waite, *ibid.*, pp. 178–179, pl. 23, fig. 4, monotypic); McCulloch, Australian Zool. 2(pt. 3): 102, fig. 276a. 1922.

[3] *Schizochirus* Waite, Rec. Australian Mus. 5(pt. 4): 240. 1904 (genotype, *Schizochirus insolens* Waite, *ibid.*, pp. 242–243, figs. 33, 34, pl. 26, fig. 3, monotypic); McCulloch, Australian Zool. 2(pt. 3): 102, fig. 277a. 1922.

[4] *Tewara* Griffin, Trans. Proc. New Zealand Inst. 63(pt. 2): 174–176, pl. 25, upper fig. 1933 (genotype, *Tewara cranwelli* Griffin).

[5] *Crystallodytes cookei* Fowler, Occ. Pap. B. P. Bishop Mus. 8: 390–392. 1923 (type locality: Laie Beach, Oahu), Fowler, Fishes of Oceania, Mem. B. P. Bishop Mus. 10: 426, fig. 60. 1928; Pietschmann, B. P. Bishop Mus. Bull. 156: 44, pl. 16, B. 1938.

[6] *Trichonotus* Bloch in Schneider, Syst. Ichthy., p. 179. 1801 (genotype, *Trichonotus setiger* Bloch in Schneider).

8*b*. First rays of dorsal and last rays of pelvics not elongate or filamentous..... *Hemerocoetes*[7] Cuvier and Valenciennes; *Creedia*[7] Ogilby; *Lesueurina*[7] Fowler; *Squamicreedia*[7] Rendahl

7*b*. Gill membranes broadly joined to isthmus, gill opening mostly restricted to sides; dorsal rays 60; anal 37; pectoral 14 or 15; pelvics? I, 4; scales minute, not visible on young; no lateral line; anus under twenty-fifth dorsal ray; 11 branched rays in caudal fin (15 jointed rays) (PARAGOBIOIDINAE)..... ..... *Paragobioides*[8] Kendall and Goldsborough

Kraemeria Steindachner

Kraemeria Steindachner, Akad. Wiss. Wien **115** (Abt. 1): 41. July 1906 (type, *Kraemeria samoensis* Steindachner).

Vitreola Jordan and Seale, Bull. U. S. Bur. Fish. **25**: 393. Dec. 1906 (type, *Vitreola sagitta* Jordan and Seale, *ibid.*, pl. 37, fig. 1).

Psammichthys Regan, Trans. Linn. Soc. London (ser. 2), Zool., **12**(pt. 3): 246. 1908 (type, *Psammichthys nudus* Regan, *ibid.*, pl. 31, fig. 1); Psammichthyidae Regan, Ann. Mag. Nat. Hist. (ser. 8) **8**: 733. 1911.

Kraemeria bryani, n. sp.

Kraemeria samoensis Fowler (not of Steindachner), Fishes of Oceania, B. P. Bishop Mus. Mem. **10**: 425, fig. 68. 1928; Pietschmann, B. P. Bishop Mus. Bull. **156**: 43, pl. 16, A. 1938.

Holotype.—A specimen, 15.1 mm in standard length, collected by C. M. Cooke, Jr., March 1928, at Malaekahana, Oahu, Hawaiian Islands, U.S.N.M no. 109380. The following paratypes, 18 to 20 mm, were studied: 10 from Malaekahana, Oahu, May 30–31, 1926, collected by C. M. Cooke, Jr.; 7 bearing the number 4905 in the Bishop Museum and 2 now catalogued as U.S.N.M. no. 116181; 6 from Laie, Oahu, taken June 4, 1923, by C. M. Cooke, Jr., 4 having number 4904 in the Bishop Museum and 2 U.S.N.M. no. 116180; 3 from Laie Beach, Oahu, collected by C. M. Cooke, Jr., November 2, 1922, no. 4902 in Bishop Museum.

Description based on the holotype and paratypes. All measurements are expressed in hundredths of the standard length, those for the holotype out-

---

Taeniolabrus Steindachner, Sitzb. Akad. Wiss. Wien **55**: 713. 1867 (type, *T. filamentosus* Steindachner).

Taeniolabrus marleyi Smith, Trans. Royal Soc. South Africa **24**(pt. 1): 4–6, pls. 1, 2. 1936 (type locality: Durban).

[7] *Hemerocoetes* Cuvier and Valenciennes, Hist. Nat. Poiss. **12**: 311. 1837 (type, *Callionymus acanthorhynchus* Forster).

Creedia Ogilby, Proc. Linn. Soc. New South Wales **23**(3): 298. 1898 (type, *Creedia clathrisquamis* Ogilby, McCulloch, Australian Zool. **2**(pt. 3): 101, pl. 31, fig. 275a, of *Creedia clathrisquamis* Ogilby. 1922).

Hemerocoetes haswelli Ramsey, Proc. Linn. Soc. New South Wales **6**: 575. 1881. (type locality: North Head of Port Jackson).

Lesueurina Fowler, Proc. Acad. Nat. Sci. Philadelphia, 1907, p. 440 [type, *Lesueurina platycephala* Fowler (*Lesueurella platycephalus* Fowler, misprint)].

Squamicreedia Rendahl, Svenska Vet. Hand. **61**(9): 20. 1921 (type, *Squamicreedia obtusa* Rendahl).

[8] *Paragobioides* Kendall and Goldsborough, Mem. Mus. Comp. Zool. **26**(7): 324, pl. 6, fig. 2. 1911 (type, *Paragobioides grandoculis* Kendall and Goldsborough); Fowler, Acad. Nat. Sci. Philadelphia Monog. **2**: 206–207. 1938.

side the parentheses and for the paratypes within parentheses. Standard length 15.1 (19.5; 19.7; 20.3 mm); length of head 29.8 (25.4; 25.4; 27.0); greatest depth 10.0 (11.6; 9.7; 11.8); diameter of eye 1.3 (2.0; 1.5; 2.0); length of snout 3.3 (3.5; 5.1; 4.4); length from tip of lower jaw to rear edge of maxillary 5.8 (–; –; 6.9); length from tip of lower jaw to rear edge of maxillary 8.6 (8.1; 8.6; 9.4); length from tip of snout to anus 53 (–; 56.4; 57.2); length from snout to origin of dorsal fin 31.7 (–; –; 30.3); length of longest pelvic fin ray (10.6 (10.1; 11.6; 11.8); length of longest pectoral fin ray 4.0 (4.6; 4.0; 3.9); length of longest caudal fin ray 15.9 (14.7; 16.3; 15.7); postorbital length of head 22.5 (19.8; 18.8; 19.7).

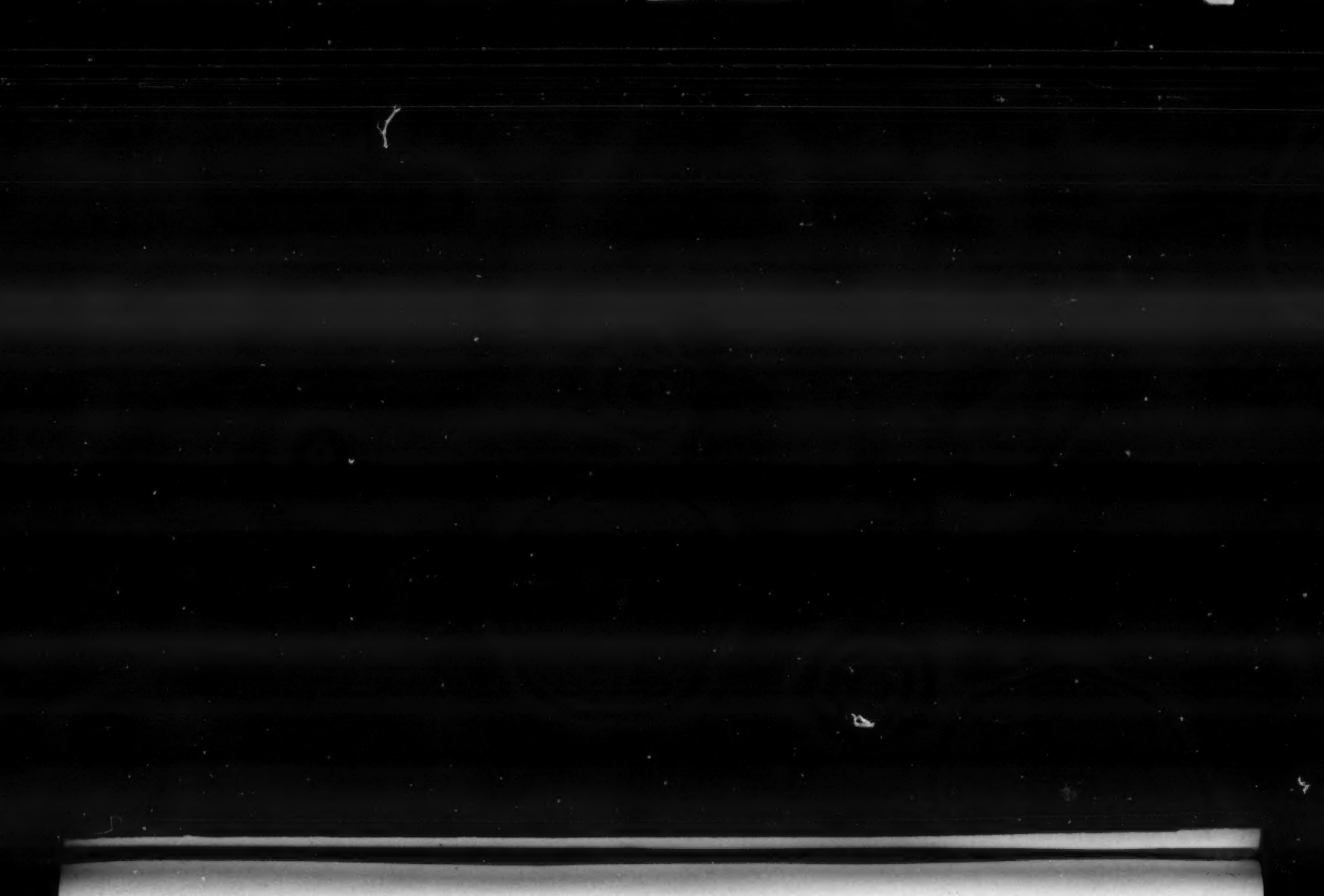
The following counts were made: Dorsal fin rays 19(4); 20(12); the numbers in parentheses indicate the number of counts; anal rays 12(2); 13(3); 14(12); 15(1); pectoral rays 3(9); 4(24); 5(2); pelvics always I, 5.

The dorsal fin almost equal distance between rear border of orbit and origin of anal fin or over the tips of the pelvic fins; the anal fin origin is under the 8 or 9 dorsal fin ray; the operculum covers the base of the pectoral fin and is attached to it dorsally; the opercular apparatus is not emarginate to fit around the bases of the pelvic fins; gill membranes are narrowly attached to the isthmus, and the gill opening does not extend as far forward as in *Crystallodytes* or *Chalixodytes;* the body and head are scaleless, and there is no trace of a lateral line; the rays in the dorsal, pelvic, and pectoral fins are unbranched; the first 6 dorsal rays and the first anal ray lack the cross marks or joints; the next to the inside ray of the pelvic fin is longest and the fifth

Fig. 1.—*Kraemeria bryani*, n. sp. (not *K. samoensis* Steindachner), after Pietschmann, 1938, pl. 16, fig. A.

ray is of about equal length; the lower margin of the lower lip, the lower margins of the suborbital and the lower margin of the preopercle are papillate; the lower jaw is longer than upper and the mouth is oblique, the tip of the lower jaw is fleshy and is pyramidal in shape with the apex pointing forward and ventrally; the eyes are close together in the top of the head; the premaxillary is not protractile, the tip of the snout has a frenum; tongue bilobed at tip.

The color has faded in alcohol and no pigmented areas are visible. The eyes are blackish.

This species differs from others in the genus *Kraemeria* in having but 3 to 5 pectoral fin rays instead of 7 or 8 as found in *Kraemeria samoensis* Steindachner and *Kraemeria samoensis merensis* Whitley (Rec. Australian Mus. 19: 244–246, fig. 11. 1935).

Named *bryani* in honor of my good friend E. H. Bryan, curator of collections, Bernice P. Bishop Museum, Honolulu.